National Center for Remanufacturing and Resource Recovery (NCR³)

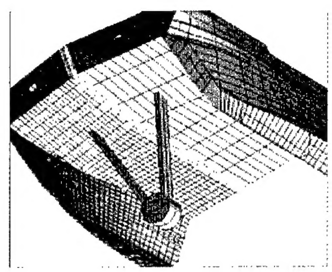
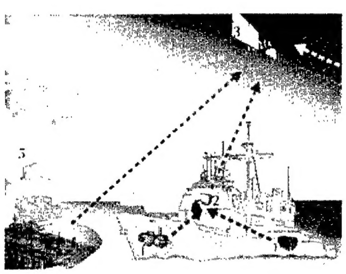
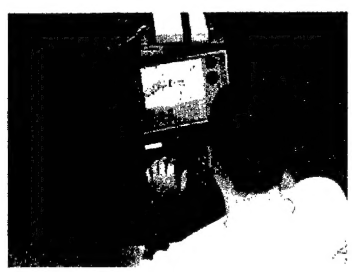
ROCHESTER INSTITUTE OF TECHNOLOGY

29 Mar 2004

Office of Naval Research
Grant No. N00014-99-1-0154

FINAL REPORT



DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

Best Available Copy

20040329 060

National Center for Remanufacturing and Resource Recovery (NCR³)
Rochester Institute of Technology
133 Lomb Memorial Drive ■ Rochester, NY 14623-5608
phone: (585) 475-6091 ■ fax: (585) 475-5455 ■ www.reman.rit.edu

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
29-03-2004

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
Dec. 1998 to Dec. 2003

4. TITLE AND SUBTITLE
~~Conversion and Remanufacturing of SES200 to Slice Platform~~

~~Modernization Through Remanufacturing Conversion (Phase I-III)~~

~~Defense Modernization and Readiness~~

5a. CONTRACT NUMBER
N/A

5b. GRANT NUMBER
N00014-99-1-0154

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)
Dr. Nabil Nasr, Mr. Scott Valentine,

Dr. Michael Haselkorn, Dr. Michael Thurston

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Dr. Nabil Nasr
National Center for Remanufacturing and Resource Recovery
Rochester Institute of Tech.
111 Lomb Memorial Drive
Rochester, NY 14623-5608

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Dr. Paul Rispin
Office of Naval Research
Ballston Center Tower One
800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSOR/MONITOR'S ACRONYM(S)

ONR 362

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release. Copyright information included.

13. SUPPLEMENTARY NOTES
None

14. ABSTRACT
The National Center for Remanufacturing and Resource Recovery (NCR3) has successfully demonstrated technologies that are able to enhance the performance of defense weapons and support systems, while smartly managing total life-cycle costs. For more than five years, NCR3 has collaborated with Department of Defense organizations, such as the Office of Naval Research, Naval Air Systems Command, Marine Corps Systems Command, Naval Air Depot – Jacksonville, Program Manager – Light Armored Vehicle, and Marine Corps Combat Develop Command, in developing real-world solutions for several major systems. For these organizations, NCR3 has developed remanufacturing and conversion processes, programs to predict equipment health and failure, life-cycle technology insertion, material analysis technologies to predict service-life.

15. SUBJECT TERMS
Remanufacturing, Life Cycle Analysis, Diagnostic, Prognostic

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Dr. Nabil Nasr
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
UNCLASS	UNCLASS	UNCLASS	U.U.	1	585-475-5106

Executive Summary

The National Center for Remanufacturing and Resource Recovery (NCR^3) at Rochester Institute of Technology was originally awarded the grant (N00014-99-1-0154) from the Office of Naval Research for the period December 1998 to June 2000. The successful completion of the initial project led to four additional extensions covering a total period of five years ending December 2003. This final report is provided in accordance with the grant requirements upon the successful completion of the original grant including its extensions.

The National Center for Remanufacturing and Resource Recovery (NCR^3) has successfully demonstrated technologies that are able to enhance the performance of defense weapons and support systems, while smartly managing total life-cycle costs. For more than five years, NCR^3 has collaborated with Department of Defense organizations, such as the Office of Naval Research, Naval Air Systems Command, Marine Corps Systems Command, Naval Air Depot – Jacksonville, Program Manager – Light Armored Vehicle, and Marine Corps Combat Develop Command, in developing real-world solutions for several major systems. For these organizations, NCR^3 has developed remanufacturing and conversion processes, programs to predict equipment health and failure, life-cycle technology insertion, material analysis technologies to predict service-life, and more.

The efforts conducted by the National Center for Remanufacturing and Resource Recovery were separated into four programs areas, with each program encompassing numerous related projects. Modernization through Remanufacturing and Conversion, Material Aging, Life-Cycle Engineering and Economic Decision Systems, and Asset Health Management were the major programs supported by the grant from ONR.

1. Modernization through Remanufacturing and Conversion (MTRAC) has been implemented in collaboration with the Office of Naval Research for several Navy and Marine Corps programs with significant measurable success. Using the RIT-developed conversion plans for the SES-200, the Navy was able to save 80 percent over the new construction alternative. Remanufacturing is a powerful approach to sustaining and advancing technological systems. It is often conducted through a series of steps, including disassembly, cleaning, inspection, refurbishment, technology upgrade, assembly and testing to original or enhanced specifications. Often, remanufactured systems are upgraded with the advanced features of today's equipment. Unlike recycling, where only the material value of a product is recovered, remanufacturing captures the material value as well as the labor and capital investment of value-added operations that took place during original production. The efforts conducted under this grant further develop the technology evaluation and insertion tools that lead to additional significant cost savings and performance enhancements on a wide variety of military platforms.

2. Material Aging is the change in the physical appearance, dimensions, or physical and mechanical properties of a component during its service life. These changes limit the useful life of the component and drive many of the critical decisions that face major systems program managers as they seek to extend the useful life of their platforms. Corrosion, stress fractures and weakening, and catastrophic material or structural failures are all serious problems that must be continuously addressed. Material aging studies have been performed on LAV and HMMWV components to characterize the material aging modes. This information will then be used to improve the performance of these components and to develop the prognostics used in the asset health management program. We have also begun structural and material analysis efforts on the EA-6B Prowler, managed by Naval Air Systems Command, Naval Aviation Depot, Jacksonville.

3. LEEDS™ (Life-Cycle Engineering and Economic Decision System) is a total system approach to optimizing life-cycle system performance through planned modernization and step improvements in technological capabilities. LEEDS™ was initially developed and demonstrated for the remanufacture of the SES-200, a surface effect ship. LEEDS™ is currently being applied to the AGOR-26, a newly commissioned oceanographic research vessel, as well as on several USMC ground vehicles with benefit of lower life-cycle costs and tools to improve decision support for maintainers. This application will help in the life-cycle maintenance and operation of these military platforms.

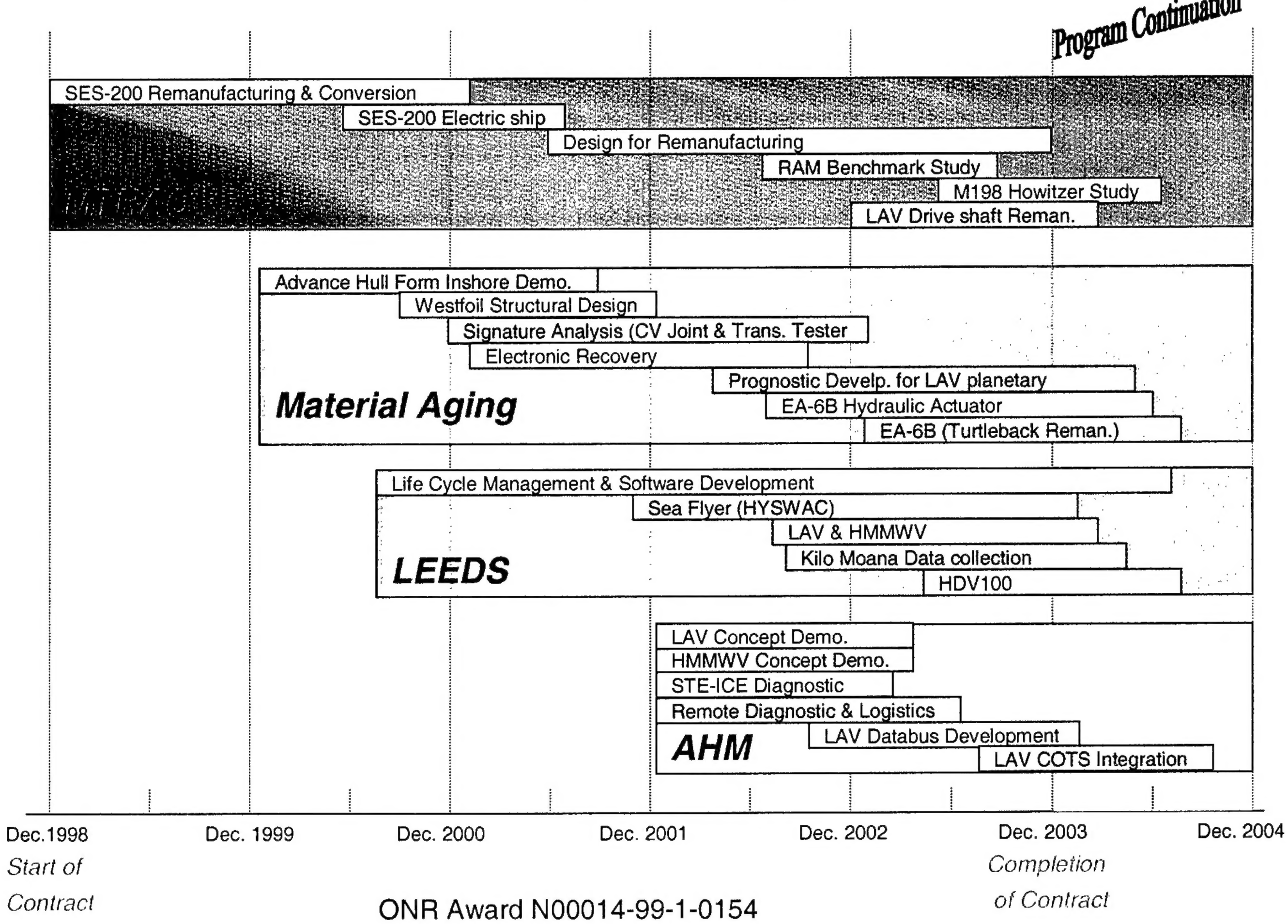
The evolution of LEEDS™ focuses on improving an owner/operator's decisions relating to equipment life-cycle costs throughout system operating life, not only at end-of-life. LEEDS™ serves as an efficient method for the identification, collection and storage of pertinent system specifications from initial design and build activities. These specifications, in addition to the wealth of condition, performance and cost data that accumulates during systems' life cycles, will be warehoused in a centralized repository and will allow LEEDS™ to serve as an on-board maintenance support tool as well as a high-level performance monitor of key systems. This will enable users to assemble and manage enormous quantities of design, cost, condition, and performance data. Performance and cost alternatives will be identified and updated easily by enabling users to frequently revisit maintenance, modernization, remanufacturing, operating costs and other variables throughout the life of a system.

4. Asset Health Management is a holistic approach to managing the operation and maintenance of complex equipment. At the core of an asset health management system is an ability to monitor the condition, degradation, and health of the equipment. Monitoring data can be analyzed manually or automatically to detect equipment health trends. The ultimate goal is the ability to correctly determine the maintenance and repair needs of the equipment, and to schedule maintenance prior to failure and such that the operation of the equipment is minimally impacted. Our technology development starts at the platform,

determining the appropriate information (sensors and signals) that is required to detect and diagnose failure and to allow trending of degradation (and ultimately prognostics – remaining life assessment). Methodologies have been developed for this initial platform assessment and applied to legacy Marine Corps ground vehicles (HMMWV-High Mobility Multi Wheeled Vehicle and LAV-Light Armored Vehicle). Implementation of on-board monitoring requires the integration of monitoring algorithms in hardware/software systems. A concept demonstration architecture was developed and implemented on the HMMWV and LAV. Electrical system diagnostics were developed for both platforms along with high level system functional assessments. Technology was also developed to support transfer of platform monitoring data to centralized fleet monitoring location. This remote diagnostics capability was also implemented for both platforms. The platform health, fuel and ammunition status, and the GPS location were reported over an RF wireless network. Finally, the concept architecture has been transitioned to a fieldable monitoring architecture. The LAV monitoring system was transitioned to a databus based design using hardened system components. The second generation architecture was designed for compliance with the Integrated Data Environment being developed by PM-LAV. Technology development needs that still need to be addressed include the development of robust prognostic (failure prediction) methodologies, this will include fleet-based trending and data analysis approaches. In addition, a better understanding of electronics degradation will be developed in order to support an ultimate goal of prognostics for electronics equipment.

The four programs and their respective projects are highlighted in the chart titled "*Project Summary*" and then more fully developed in the chapters of this report. This chart represents the projects conducted under the ONR grant N00014-99-1-0154 from December 1998 through December 2003. The continuations of effort are represented to illustrate the growth under a separately funded grant supporting the Office of Naval Research.

Project Summary



ONR Award N00014-99-1-0154

Within the four major programs shown above, a total of 24 projects were initiated. These projects in some cases were conducted to directly support the Office of Naval Research and in other situations, projects were directly supporting a particular warfare specialty office (USMC – Program Manager for Light Armored Vehicle for example). Each project was undertaken with a clear understanding of the problem and applied technologies were successfully developed at NCR^3 to solve the issues. Through applying new technologies, NCR^3 enabled significant technology advancement for legacy platforms and improvement of their operational readiness and availability. In addition, tremendous cost savings were realized through these efforts. Some of the savings are as shown:

- **Remanufacturing of an existing ship (SES-200)**

Cost of an equivalent new ship	$40.0 Million
Cost to remanufacture existing platform	$ 7.4 Million
Total Savings	*$32.6 Million*

- **Light Armored Vehicle cost impact**

Total Maintenance Cost Reduction	$2.5 Million / year
System development & Up keep	($0.4 Million / year)
Savings over 20 years	*$41 Million*

- **EA-6B Prowler Turtle back cost impact**

Existing design, traditional supplier	$80K / each
RIT redesign, commercial aviation manufacturer	$12 K / each plus 150K set up
Savings with 50 part buy	*$3.25 Million*

- **Light Armored Vehicle propeller shaft remanufacturing**

The cost for a new shaft through DLA	$600 / each
Cost to remanufacture existing	$150 / each
Savings per year for the Depot	*$126,000.00*

- **M198 Howitzer (155 mm) Life extension study**

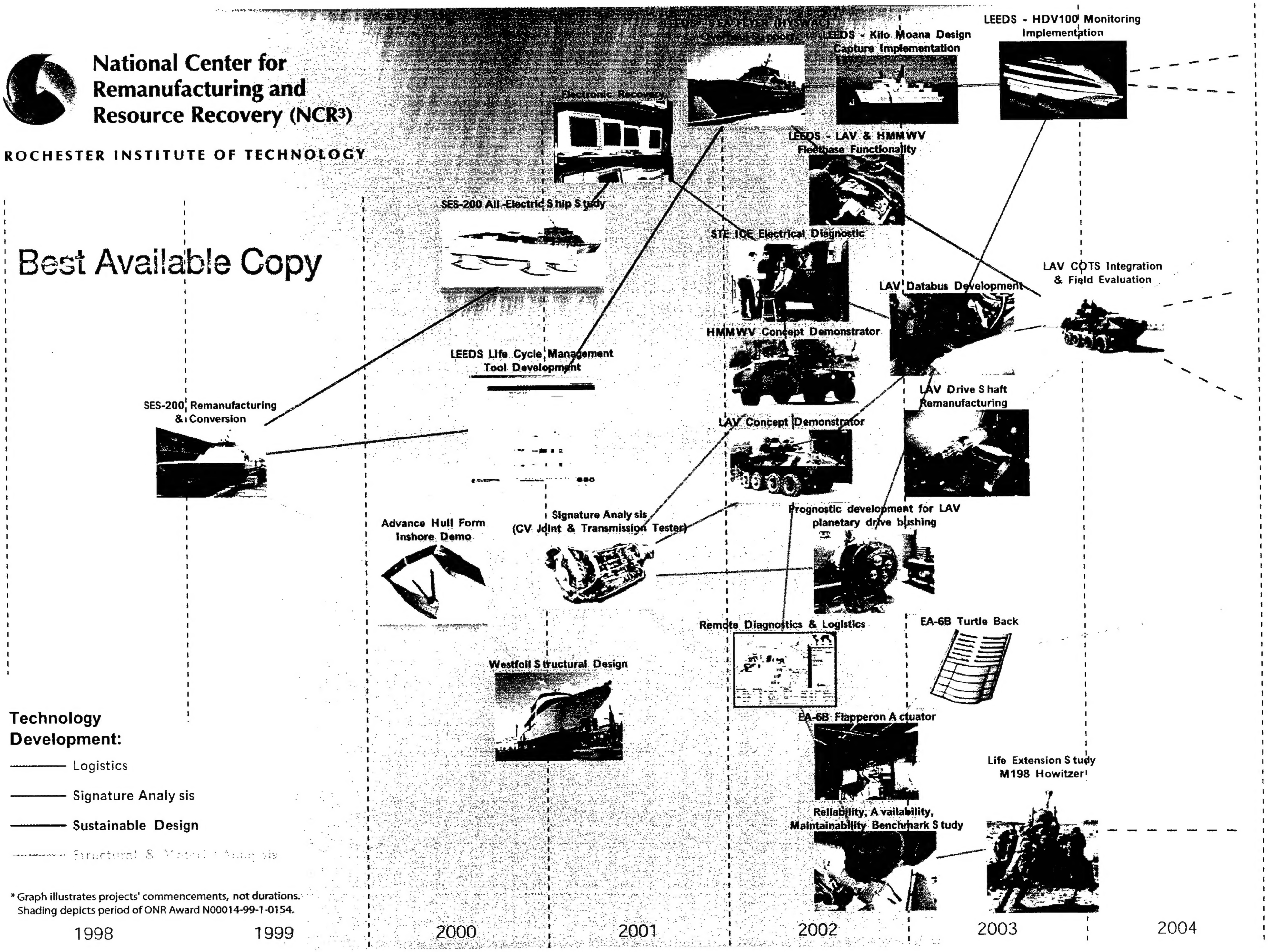
Annual value of 504 Howitzer with a 20 year life	$26 Million
Annual value of 504 Howitzer with a 23 year life	$22.6 Million
Savings achieved by extending the platforms life	*$3.4 Million*

A five year histogram (shown on the next page) illustrates the related development of the four programs from the beginning of the original grant. From the initial work conducted on the ship SES-200, the Office of Naval Research funded activities have grown to include ground vehicles, aircraft, as well as several other ships. In fact, in each area, sea land and air, additional projects are being identified and developed through new funding, leveraging earlier project efforts to support emerging issues on evolving platforms.

The National Center for Remanufacturing and Resource Recovery has proven to be a preeminent leader in the field of remanufacturing and system upgrades. The Center's continued achievement with industrial customers provides a unique perspective into commercial total life-cycle issues that are easily translated into proven successful solutions for the Department of Defense.

National Center for Remanufacturing and Resource Recovery (NCR3)

ROCHESTER INSTITUTE OF TECHNOLOGY



* Graph illustrates projects' commencements, not durations.
Shading depicts period of ONR Award N00014-99-1-0154.

Introduction to National Center for Remanufacturing and Resource Recovery at Rochester Institute of Technology

The National Center for Remanufacturing and Resource Recovery (NCR^3) at the Rochester Institute of Technology is internationally recognized as a leading center for research and developing in design for the life cycle, systems sustainment, remanufacturing / conversion and upgrade technologies.

NCR^3 has broad experience in engineering issues, such as signature analysis, material fatigue and stress, as well as technology insertion, reverse engineering, condition assessment and total cost of ownership, all of which have great value when applied to major systems design. This unique perspective, gained from exposure to the consequences of earlier engineering trade-offs, provides NCR^3 with both experience and technical expertise to help major systems design teams make engineering trade-off decisions today.

NCR^3 originated in 1990 from a collaborative effort of RIT's College of Engineering, representatives form industry and several federal laboratories. Today, NCR^3 is a strong, professional team of full-time engineers, augmented by RIT faculty and students. It develops its agenda based on industry needs and with industry inputs.

In the spring of 1997, NCR^3 moved to its current home at the Center for Manufacturing Studies (CIMS). The 170,000 square-foot facility houses $30 million of contemporary equipment and supports solution developments in technology bays, specialized applied technology laboratories and a state-of-the-art training center.

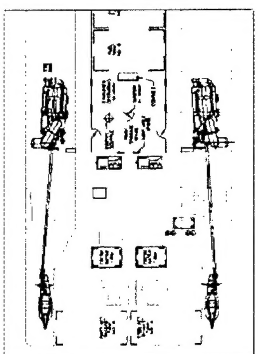
Some of NCR^3's past and current clients include Eastman Kodak, Xerox, Detroit Diesel, Peugeot, Navatek, Mack Truck, the Office of Naval Research, the Environmental Protection Agency and the Department of Energy.

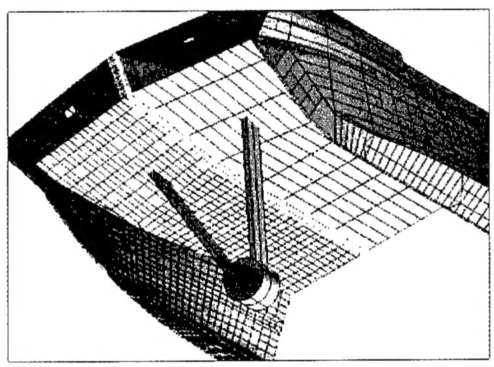
Rochester Institute of Technology (RIT)

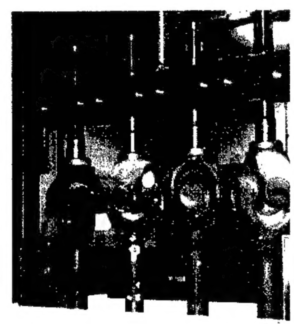
"Practical" and "applications oriented" are two phrases commonly associated with Rochester Institute of Technology, which is one of the nation's leading private technical universities. Emphasizing career oriented education and service to industry; RIT has one of the nation's largest cooperative education programs. With more than 45 percent of its graduates working in manufacturing, RIT has developed particular academic expertise in such areas of concerns to industry as engineering, computer science, printing and publishing, quality and applied statistics, business and imaging science.

MTRAC

Modernization Through Remanufacturing and Conversion







Program 1: Modernization through Remanufacturing & Conversion (MTRAC)

As the United States continues to be a leader in global peace, it is apparent that our future forces are going to be using older equipment for longer periods of time. A balance must be realized between declining budgets and the need to revitalize our aging equipment in order to provide advance technology insertions into the front line weapon systems. Unlike most firms in the private sector, the many branches in the Department of Defense (DoD) manufacture, consume and maintain many of its own systems. Rapid advances in technology and ever shortening system life-cycles demand quick response times for conversion and/or upgrades of existing systems. One of the answers to modernizing our defense resources while working with a shrinking funding source is through a practice that the commercial sector has embraced for forty years called **remanufacturing**. Remanufacturing is a highly effective strategy of restoring used durable products to a "like new" condition, while enabling technology upgrades, at a substantial savings to the end user.

Modernizing systems by applying remanufacturing principles is the key to fielding new technologies at low cost and low risk and with improved performance in a shorter lead-time. Operating costs and environmental costs can be kept low by modernizing legacy systems instead of purchasing new systems outright. Additionally, through selective approaches in remanufacturing, improvements will be garnered in the areas of reliability, availability and maintainability (RAM) of systems. This cost-effective way of producing new military platforms can minimize the costs of modernization and upgrades. It satisfies technology needs at critical moments while reducing lead times for procuring new systems. Modernizing existing systems with remanufacture is a way to maximize yesterday's investments tomorrow. By making equipment contribute more value for longer; it insures the investment by providing a way to test technologies before investing in them.

The National Center for Remanufacturing and Resource Recovery (NCR^3) has been conducting ongoing research to develop technologies to modernize equipment through remanufacture and conversion. MTRAC is an organized approach for integrating remanufacturing into the full life-cycle of a product or system. The MTRAC program has developed tools and processes to aid in design for remanufacturing, remanufacturability assessments, cost estimations for upgrades and advanced technology insertions. This program has delivered to ONR cost-effective, superior techniques to assist in upgrading, converting and maintaining a system once it is deployed.

NCR^3 uses a unique combination of expertise in analysis of material failures, analysis of structural integrity and performance, diagnosis of product health and prediction of remaining life, and end-of-life recovery to help the Department of Defense manage their

deployed asset investments. The MTRAC innovative approach to the life-cycle of a product emphasizes the importance of improving the Reliability, Availability and Maintainability (RAM) issues that would normally plague legacy platforms.

Since many systems employed by the DoD are costly to manufacture and maintain, strategies to reduce these costs have the potential to conserve significant financial resources. Remanufacturing is a powerful approach to sustaining and advancing technological systems. It is often conducted through a series of steps, including disassembly, cleaning, inspection, refurbishment, technology upgrade, assembly and testing to original or enhanced specifications. Often, remanufactured systems are upgraded with the advanced features of today's equipment.

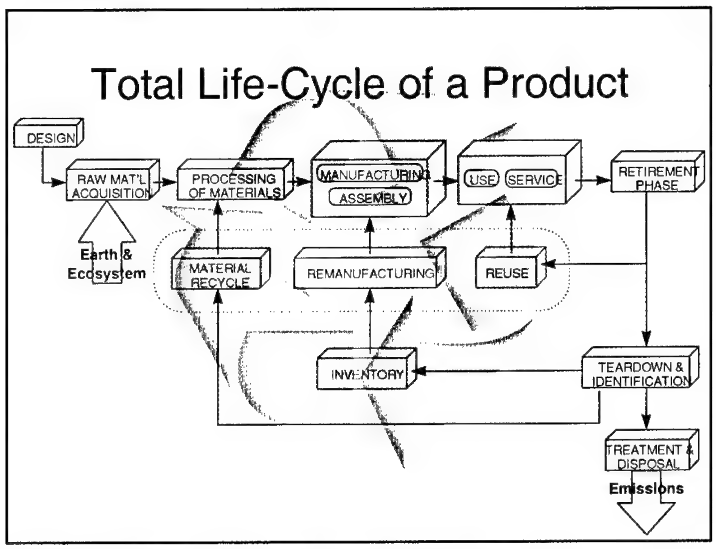


Figure 1 – Life-Cycle of Systems/Equipment

Remanufacturing serves a strategic goal for satisfying technology needs at critical moments while reducing lead times of procuring new systems. It also does not require the same resources needed for the manufacture of new systems, so remanufacturing operations can be done much closer to the system's point of use. Unlike recycling, where only the material value of a product is recovered, remanufacturing captures the material value as well as the labor and capital investment of value-added operations that took place during original production.

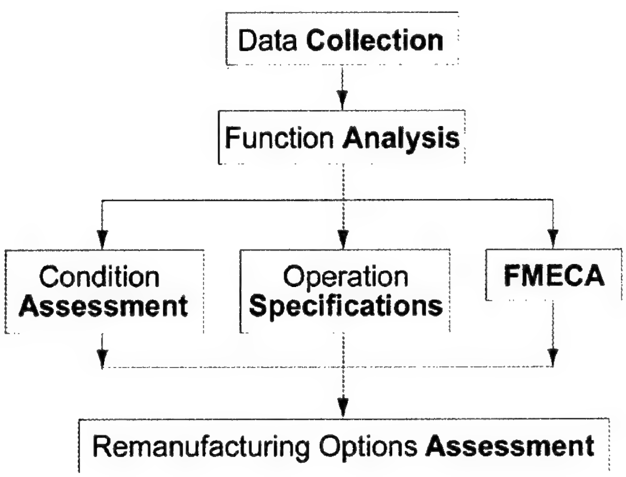
In order for a product to be remanufactured in the best possible manner, it needs to be designed for remanufacture from the start. A number of design strategies have been developed to facilitate remanufacturing. They include: avoidance of permanent fastenings such as welding or crimping; making designs modular so that assembly/disassembly times are minimized, and; standardizing fasteners to reduce assembly/disassembly and material handling complexity.

Remanufacturing can be thought of as a single stage of the life-cycle of a system or piece of equipment, as depicted in Figure 1. Operations can be made more efficient through the use of support technologies and methodologies. For example, reverse engineering techniques can be used to generate original equipment design specifications and

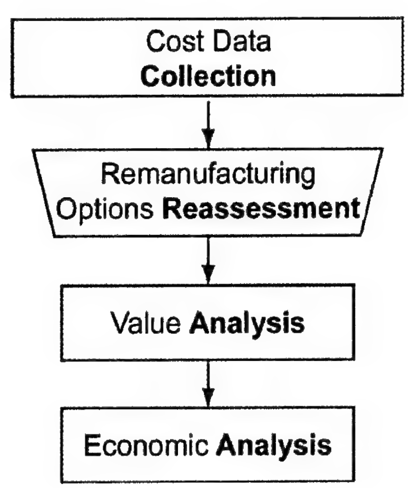
tolerances when this information is unavailable at the remanufacturing stage. Design capture can be utilized to collect information from equipment at end-of-life and feed back improvements to the design process. Life-cycle costing methodologies can support intelligent design selection by uncovering cost information up to and including system end-of-life.

Modernization through Remanufacturing and Conversion provides the tools that can be applied to the remanufacture of ships, aircraft, tanks, trucks, and a variety of other vehicles, platforms, and equipment. MTRAC provides a method for the procurement of products that meet or exceed new product standards, incorporate technological advances and reduce the total system cost.

A Remanufacturing process was developed and implemented on the SES-200 vessel, owned by the Office of Naval Research. This process was developed in two parts to evaluate separately the engineering and economic feasibility of the project.



The engineering feasibility, as shown in the diagram to the left, collected data on the platform, then through a functional analysis, condition assessment, failure mode effect and criticality study and review of the forward going operational specifications provided the available remanufacturing options. The process of balancing each of these inputs to derive the appropriate remanufacturing option assessment has evolved into an algorithm based application.



The next part in the remanufacturing tool is a careful examination into the cost structure for each of the potential "remanufacturing options" as determined in the engineering feasibility section. The economic feasibility would follow the process as illustrated in the chart to the right.

Each of the potential remanufacturing options would have a cost determination developed to place that specific part into like new condition. The cost determination for each option would be compared against one another in a value analysis, which would allow the equipment users to weight what factors were more important or less important to them. Such

factors were items like, life expectancy, consumable cost, acquisition cost, and environmental impact. The weighting of these factors would be used as an input to the economic analysis which would combine the cost determination with the value analysis weights and determine the most appropriate remanufacturing option. The best remanufacturing options were then rolled up on each component to create the overall cost to remanufacture the platform. By applying these process to the SES-200 vessel the Office of Naval Research was able to calculate the expected cost outlays to return the ship to a like new condition.

These tools sets and other processes developed in the MTRAC program were implemented across the following 6 projects:

• SES-200 Remanufacturing & Conversion	Sponsor / ONR
• SES-200 All Electric Ship study	Sponsor / ONR
• Design of Remanufacturing tool development	Sponsor / ONR
• Reliability Availability Maintainability Study	Sponsor / MARCORSYSCOM
• M198 Howitzer life extension study	Sponsor / MARCORSYSCOM
• Light Armored Vehicle shaft remanufacturing	Sponsor / USMC Depot Albany, GA

These projects are fully developed in the next section of this report.

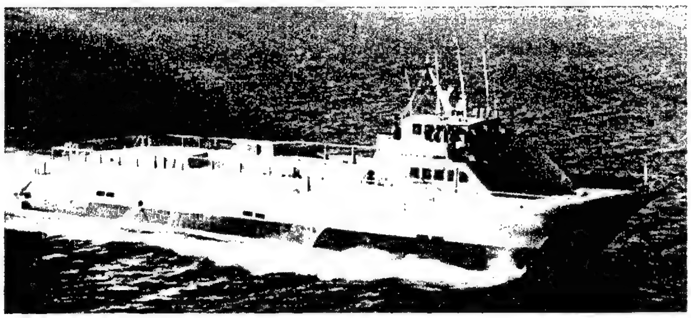
Modernization Through Remanufacturing and Conversion

PROJECTS

Project Title: SES-200 Remanufacturing and Conversion

Problem:

Remanufacturing is an engineering discipline that extends beyond rebuilding or overhauling. Specific steps, methodologies and analysis tools are used to produce systems that perform equal to or better than new. Often remanufactured hardware is upgraded with advanced features of today's equipment, which is a way to maintain the military's technological superiority at a fraction of the procurement cost of a comparable new system. The remanufacturing philosophy provides greater readiness, reduces total life cycle cost and extends the useful life cycle of existing systems.



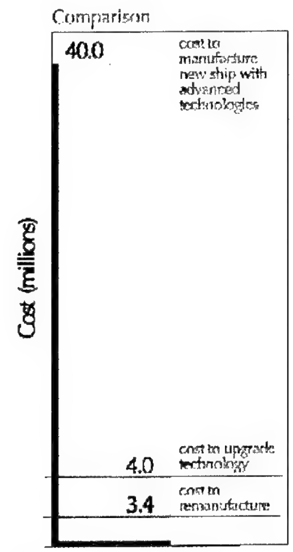
In order to take advantage of advanced technologies with less risk and lower financial and environmental costs, the Office of Naval Research charged NCR[3] with the investigation of the remanufacture and conversion of an existing ship (SES-200) to a ship with an advanced hull form (SLICE technology). Remanufactured SES vessels may be used by the Navy to conduct communications, logistics and other combat support activities in the near-shore littoral region.

Approach:

This project included a feasibility study and engineering analysis for the remanufacture of an existing SES-200 and technology upgrade to a SLICE-equivalent hull form. Investigative assessments of the SES-200 were conducted to evaluate the technical and economic feasibility of remanufacturing. Reverse engineering methods and technologies were used to gather the data crucial to these assessments. Part conditions, failure modes, operational specifications, current regulations and alternate recovery options were investigated in order to recommend the optimal remanufacturing plan for each ship system.

An information database was developed to automate the data collection, analysis, and decision-making for the SES-200 remanufacturing initiative. This database was accessible via the Internet and provided access to the resident data, engineering analysis and drawings from remote locations.

CFD models were developed to optimize the hydrodynamic shape of the pod bodies to provide sufficient buoyancy with minimal drag. Arrangement studies of system and component interface and ship architecture were conducted through construction and analysis of 3-D solid models. These models also provided geometry for finite element analysis. Each individual section was constructed from bulkhead frames and girders, then connected and assembled to form the vessel's infrastructure. Pod and strut assemblies were subjected to several load conditions using FEA to refine and enhance the concept design. Stress distribution from the pod and strut assemblies to the existing vessel was analyzed to verify the structural integrity of the SES-200 and to propose structural modifications required to meet design stress limits.



Example of Cost Savings from Naval application:

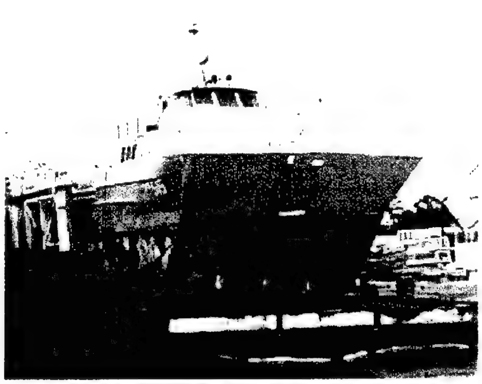
$32.6 Million

Results:

NCR[3] generated design concepts and economic models to justify the remanufacturing and conversion of the SES-200 to provide ONR with a test vehicle for evaluating SLICE technology. The final cost of ship remanufacturing and technology insertion was estimated to be twenty-percent of the cost to manufacturing an equivalent SLICE vessel.

Considerable engineering groundwork was conducted for the conversion of existing SES vessels to SLICE-equivalent vessels using multidisciplinary analysis tools such as structural and material analyses, finite element analysis, and computer-aided engineering. Since the completion of this project, actual conversion of the SES-200 into the HYSWAC (Hybrid Small Water Plane Area Craft) took place at Navatek LTD. shipyards, in Honolulu, HI.

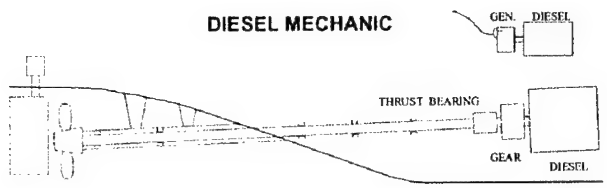
Because of the favorable results from the remanufacturing feasibility study, and due in part to the successful conversion to HYSWAC, the evaluation methods for the technical and economic feasibility of remanufacturing and converting the SES platform were validated. These methods have served as the genesis for what has become to be referred to as LEEDS™ (Life-cycle Engineering and Economic Decision System). As a result, the LEEDS™ initiative has become a continued focus of research and development, and has continued to be maintained and demonstrated aboard the HYSWAC (recently renamed SeaFlyer) as the ship undergoes performance trials.



Project Title: SES-200 All Electric Ship Study

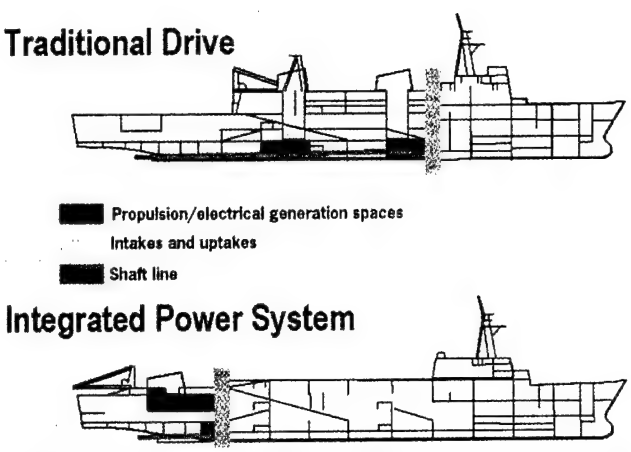
Problem:
Evaluate the integration of an all-electric propulsion system into the SES-200 to demonstrate new technologies.

NCR[3] was instructed by the Office of Naval Research to evaluate the feasibility of inserting all electric technology on-board the existing SES-200 for ship propulsion and remaining service. Also identified were the hydraulic and pneumatic systems to be replaced by similar electric driven components. The project results include cost constraints for converting the ship as well as constraints on the ship's excess carrying capacity.



Approach:
NCR[3] addressed the project goals with five major tasks: an electrical power source, drives for motors, integrated propulsion motors, electrical motors, mechanical drive systems. NCR[3] thoroughly researched the latest commercially off the shelf (COTS) advancements available for a December 2001 ship installation. They put significant effort into identifying equipment with the greatest power-to-weight ratio to maximize the ship's carrying capacity. From the evaluation NCR[3] identified the most promising options in each category and placed a composite platform into the ship.

Typical conventional fleet propulsion systems use mature technology with known limitations. The long shaft line consumes a large volume of the ship's space and experiences energy losses through heavy reduction gears, shaft thrust bearings and auxiliary support equipment.

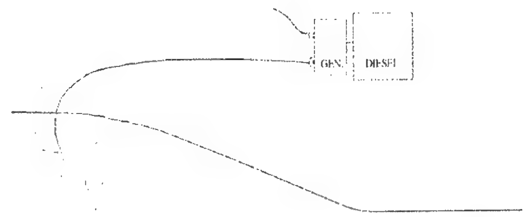


A Navsea graphic comparing two amphibious ship designs. The space saved by integrating propulsion and generating equipment could mean there would be a stateroom for every sailor.

An electric power propulsion system (EPS) would provide the following benefits:
1) Power may be used when and where it is needed, thereby maximizing combat system effectiveness and ship survivability.
2) An EPS facilitates greater use of automated systems, thereby reducing manning requirements.

3) With an EPS, machinery space is reduced, thereby allowing an increase in size and quantity of ordinances, equipment and supplies.
4) An EPS improves signature reduction and quieting capabilities through use of fewer "noisy" mechanical components.
5) Overall design and operating costs may be reduced (fuel, maintenance, logistics and manning). Commercial off the shelf (COTS) equipment is available for many systems elements, allowing bulk purchasing for many fleet wide parts.

Results:



1) NCR^3 evaluated electrical power sources including diesel/gas generators (60 Hz & 400 Hz), gas turbines and fuel cells. They determined that a Caterpillar model 3156 would provide the best power generation, considering usage of fuel consumption, install weight and output power availability. The fuel cells were considered impractical based on their limited power output of 200 kW, requiring 25 units to achieve the necessary 5000 kW for total ship consumption.

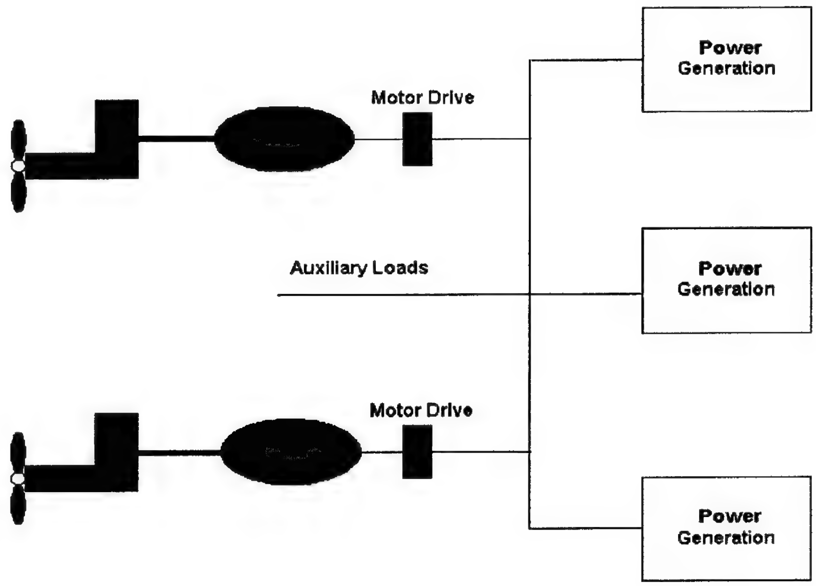
2) NCR^3 selected AC and DC drive units because they meet the requirements of the motor while being the lightest in weight. Motor drives are specifically matched to the type of motor that is being controlled. For the most part DC drives were lighter in weight compared to their AC counterparts. However, the corresponding DC motors were heavier than the AC motors of a similar rating.

3) Integrated Propulsion Motors allow the propulsion motor to be placed outside of the ship's hull, reducing spacing constraints internal to the hull. Power generators would directly feed variable speed motors that are directly coupled to the drive propeller. These azmuthing propulsion drives would provide tractor type technology 360° degrees of revolutions. Compact azipods made by ABB are available with a 2.6 MW output, however installation constraints on this smallest manufactured unit would prevent placement on the SES-200.

4) NCR^3 evaluated electrical motors in both AC and DC varieties of the size of 3000 hp and determined that the greatest opportunity exists in high temperature superconducting (HTS) motors. While still under testing, these motors have been manufactured at up to 1000 hp at one-fourth the weight of a traditional motor. However, a primary criterion in the evaluation was a December 2001 installation date and because of the new design of the HTS

motors, the 3000 hp version could not be installed by that date. NCR[3] found that an AC induction marine duty package would provide the next best power-to-weight ratio motor and drive packages.

5) NCR[3] evaluated mechanical drive systems, which are available in standard propeller, water jet systems and Z-drive configurations, and found the water jet configuration impractical due to the potential for evacuation in certain high seas at the impeller inlets. However, the Ulstein Speed Z drive has a unique capability to incorporate a reduction gear, variable pitch propeller and rudder control. An electric motor would directly couple to the input of the Z-drive enabling electric drive capability in a small package arrangement. Therefore, NCR[3] chose the Ulstein Speed Z drive as the most feasible option.



6) Cost & Weight Calculations:
NCR[3] calculated that the SES-200 conversion to an all-electric platform would cost an estimated $6.1 million. The platform would weigh 165,000 pounds (73.8 tons). The remaining capacity would be 26.2 tons.

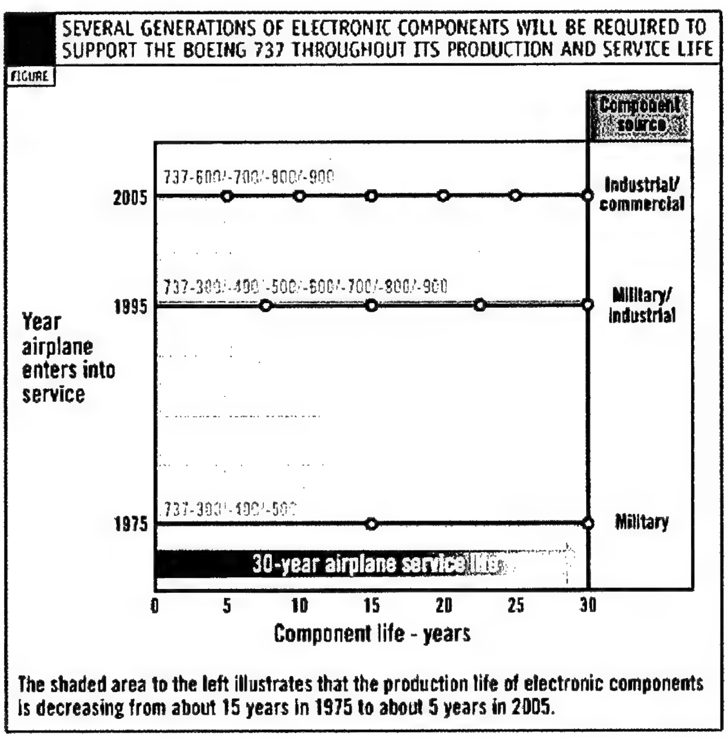
Project Title: Process for Design for Remanufacturing

Problem:

Technology innovation, while often improving product performance, reliability and safety, also comes with a price - product obsolescence. Rapid development of new technologies, advancements in design tools (CAD) and computer software enable rapid introduction of new technologies and improved product designs, often at rate where a product can be technologically obsolete by the time it enters service. This scenario is particularly evident in applications where the product is a large and requires lengthy development and production cycles, such as military and commercial transportation systems (e.g., ships, planes, and submarines). In these applications the product development cycle may be as long as 10 years from the time the product is conceived to the time it is introduced into service. During which time many changes and improvements in technology can occur that may ultimately render the product technologically deficient, or worse yet, obsolete. This problem manifests itself further, when considering the expected service life of some transportation systems may exceed 30 years, but the expected production life vital components within the platform may only be 5 years, or less.

This problem was exemplified in a recent study conducted by Boeing (see Figure 1), where it was estimated that the production life of electronic components has diminished from 15 to 5 years over the period of 1975 to 2005. As a result, several generations of electronics will need to be replaced over the production and service life of a Boeing 737 due to obsolescence.

The problem was further exemplified by the Boeing study, where it was estimated that 60 percent of the integrated circuits currently used in aerospace products may no longer be in production within 5 years, and a graphics display for military applications may be redesigned with new technology every 11 months.



The shaded area to the left illustrates that the production life of electronic components is decreasing from about 15 years in 1975 to about 5 years in 2005.

Figure 1

The objective of this project is to develop a formal Design for Remanufacturing (DFR) tool, that will increase useful product life, capitalize on emerging technologies, and minimize environmental impact through cost-effective, incremental technology integration.

To reverse the growing trend in product obsolescence, National Center for Remanufacturing and Resource Recovery developed process that will enable maximization of useful product life through application of sustainable design principles. As illustrated in figure 2 below, a design process that facilitates planned, incremental technology integration, enables a product to maintain a competitive level of performance and reliability over its lifetime, at a cost and risk substantially less than replacing the existing system with an entirely new one.

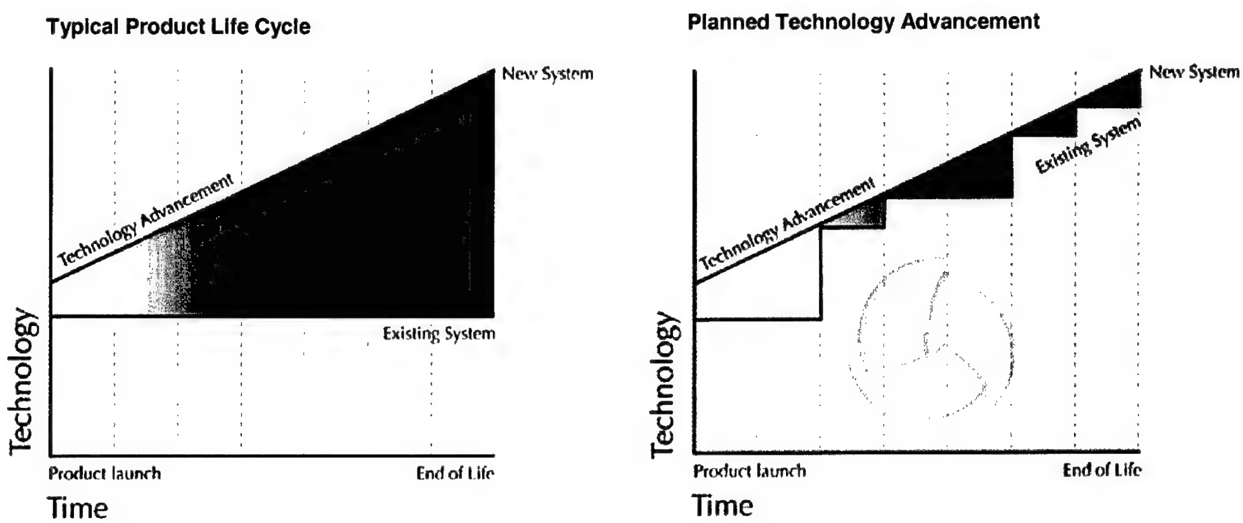


Figure 2

In addition, implementation of an DFR process, as described above, benefits the environment by reducing consumption of raw materials and energy needed to produce entirely new systems, and disposal of otherwise obsolete products.

Approach:

The development of an Design for Remanufacturing process will involved the following activities:

1.) Selection of pilot case studies to facilitate development of the process.
2.) Research of emerging technologies in areas such as materials, control systems and electronics to assess innovation cycles, trends in production cycles and estimated product life,

3.) Establishment of generic 'decision making tools' with standardized Technology Performance and Operations Impact Metrics, to enable quantitative comparison of competing technologies and design options,
4.) Development of an automated, computerized system to facilitate use of the DFR process,
5.) Validation and refinement of the process by application on additional case studies, and
6.) Demonstration and transfer of the process to DOD and industry through direct project assistance and publications.

Results:
The DFR process was applied to an automobile. This process consisted of:

- A function analysis was performed to identify basic function of system or component (e.g., structure, energy conversion, control).
- Technology Forecasting
  Research current and emerging technologies
  Predict innovation cycle and production life
- Value Analysis — Compare technologies to design requirements based on a decision Matrix with the metrics (e.g. reliability, durability, operating costs, regulations)
  - Weighting Factors of Importance
  - Level of Satisfaction in meeting Design Requirement
  - FMECA
  - Failure Modes Effects and Criticality Analysis
  - Compare Options against Metrics.

Unfortunately, for the automobile the main drivers for the insertion of new technology were cost and reliability. Thus, new technology is not inserted into a design until it totally proven out. However, this exercise did enable NCR^3 to develop a DFR process that can easily be applied to additional components or products.

Project Title: RAM Requirements, Definitions and Estimation Projects

Problem:
The National Center for Remanufacturing and Resource Recovery (NCR^3) at the Rochester Institute of Technology is providing the resources to support Marine Corps System Command's (MARCORSYSCOM) Capability Assessment Integrated Product Team. A comprehensive study has been performed to identify the factors that most affect reliability, availability and maintainability (RAM) of a few select, existing systems. The goal of this study is to provide insight to improve the readiness of these existing systems and the sustainability of future systems. This study will concentrate its efforts on the following five fielded platforms.

- Logistic Vehicle System, LVS, TAM D0209
- Amphibious Assault Vehicle, AAVP7A1, TAM E0846
- Machine Gun, 7.62mm, M240, TAM E0989
- Tractor, Medium Full-Tracked, D7G, TAM B2462
- SINCGARS, Radio Set, TAM A2070

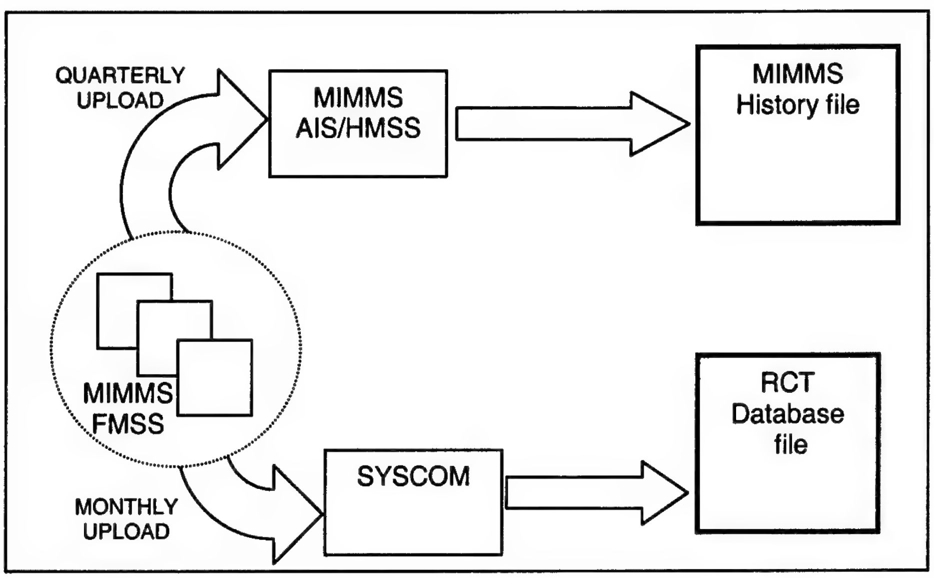
Approach:
Task One provided analyses of the four platforms for which data was provided. The analysis will review pertinent requirement documents such as Mission Needs Statements (MNS) and Operational Requirements Documents (ORD) to examine terms and methodologies for defining RAM requirements. Technical literature was provided for the Amphibious Assault Vehicle (TAM E0846), Logistics Vehicle System (TAM D0209), M240G Machine Gun (TAM E0989), and the Medium Tractor (TAM B2462). No technical information was provided on the SINCGARS Radio set (TAM A2070), preventing results under this task. Additionally, the requirements documentation regarding the Medium-duty Tractor (TAM B2462) was derived from literature on the Light Capability Rough Terrain Forklift (LCRT) and the Armored Combat Mover (M9ACE). The actual MNS and ORD for the Medium duty tractor were not available, and the other two systems were acceptable to the Study sponsor as surrogate data.

Task Two directed the study team to compare RAM estimates before equipment fielding (Task One) to RAM achieved after equipment fielding using the Marine Corps Integrated Maintenance Management Systems. The study team provided analysis of all five of the platforms for which usable data was provided. RAM metrics were calculated for the Amphibious Assault Vehicle (TAM E0846), the Logistics Vehicle System (TAM D0209), the SINCGARS Radio set (TAM A2070), the Medium Tractor (TAM B2462) and the M240 Machine Gun (TAM E0989). A set of general RAM metrics was calculated for each platform including Mean Time Before Failure (MTBF), Availability, and Mean Time To Repair (MTTR).

Task Three provided five onsite benchmark surveys. The purpose of these surveys was to identify methods and data that contribute to accurate reliability, availability and maintainability (RAM) estimates. The benchmarking study identified several potentially useful RAM methodologies. Surveys were conducted with Caterpillar, Enterprise Rent-a-Car, Xerox, Otis Elevator and Jet Blue Airway.

Results:
The MIMMS history file provides more data than the RCT for parts and labor data; the RCT database has additional values, such as the total number of down days per maintenance action (catm), which is calculated from the raw MIMMS data (not included in the MIMMS history file). These calculated values are important since extracting metrics from MIMMS data is extremely labor intensive.

The diagram below illustrates the flow of information from the FMSS to the two reports that were made available to NCR3. The quarterly upload from FMSS to AIS/HMSS provides the basis for the MIMMS historical maintenance file. The RCT database is maintained separately by SYSCOM personnel. It is updated on a monthly basis directly from FMSS.



The specified metrics for each platform are summarized in the tables below.

E0846 AAV

Reliability	MTBMCF	43.5 hours
	Mission capability	600 hours
	Probability of mission completion	0.75 for 12hr.
	Component operational life expectancy	300 hours
Availability	Operational availability	85%
Maintainability	Maintenance Ratio (MR)	0.4
	MTTR (organizational level)	2.3
	MTTR (intermediate level)	24
	Mean Logistics Delay Time	24 hours (intermediate)

D0209 LVS

Reliability	MMBF	2000 miles
	Probability of mission success	95%
Availability	Achieved	95%
Maintainability	MTTR (organizational level)	< 3 hours
	MTTR (intermediate level)	5 hours
	MTTPM	6 hours
	MR	0.23 hours/hour of operation
	MTBR (specific items)	20,000
	Probability of mission success (specific items)	0.60 at 20,000

E0989 M240

Reliability	Probability of mission success	90% 15,000 rounds
Availability	Operational Availability	94% or greater
Maintainability	MTTR	4 hours (intermediate)

B2462 D7G

Reliability	MTBF	45 hours
	Probability of mission success	80% for 10 hour mission
Availability	Achieved availability	> 82%
	Operational Availability	> 95%
Maintainability	Maintenance Ratio	0.40 hours/hour engine
	MTTR	4 hours

A2070 SINCGARS

(no data available)

The Reliability specifications shown above are generally in terms of the meter units (miles, rounds, hours) but that data is not reliable, nor is it captured in the RCT database. The calculation of the Availability metrics requires that standby time be separated from operating time, which is also not possible without the meter data. Similarly, the

Maintainability specifications are typically specified in terms of meter units. The Maintainability metrics also require that the labor data and the RCT data be available for each platform. Presently, the labor data is contained in the MIMMS history file but the RCT data is only available in the separate RCT database. Marrying these two sources is a complex manual process.

Since a direct comparison of the specified RAM values and achieved RAM values is not possible, the calculated values for each platform are presented in Appendix B. These data are presented for future analysis.

On-site surveys were conducted with Caterpillar, Enterprise Rent-a-Car, Xerox, Otis Elevator, and Jet Blue Airway Corporation. Each of the surveyed companies was identified through a rigorous selection process. Certain operating characteristics that had analogous relations to the US Marine Corps were used in the selection process to identify viable candidates. For instance, the operating processes used by fleet operators (Rental Car Companies), would provide useful process related information for the Marine Corps due to the wide number of military ground transportation vehicles they operate. The advance monitoring technology as applied by heavy machinery companies (Caterpillar and Otis elevator) could be applied to improve the operational availability of Marine Corp weapon systems. Jet Blue Airway investment in digital data collection and digital maintenance processes were identified as a mean of improving the maintainability of complex weapon systems. Lastly, Xerox application of RAM requirements & specifications for systems under development would present processes that may be valuable on future Marine Corps platforms.

The NCR^3 team provides the following list of findings that may enhance RAM specification, performance and reporting methodologies:

1. Integrated inventory management database reduces part wait times resulting in overall reduced maintenance cycle times.
2. RAM specifications expressed in terms of lifecycle cost ensure accountability of the product delivery contractor to achieve RAM performance for systems under development.
3. Real time equipment monitoring provides advance diagnostic information to maintenance personnel. In cases where the advance data allows advance diagnosis, reduced maintenance cycle times increase equipment Availability.
4. Use of knowledge base data to identify the most likely cause of failure reduces troubleshooting time results in reduced maintenance cycle times.
5. Data systems that allow instant visibility of all information and provide complete asset history enable detailed and meaningful analyses.

Project Title: M198 Howitzer Life Extension Study

Problem:
The M198 Howitzer artillery cannon currently in use by the United States Marine Corps (USMC) is due to be replaced by the completely redesigned lightweight LW155 Howitzer. The LW155 has slipped its USMC initial operational capability (IOC) from FY2002 to estimated FY2006, which necessitates that the current M198 Howitzer remains fielded up to an additional 4-5 years.

The Marine Corps System Command (MCSC) Product support team was asked to provide a Capability Assessment of the M198 Howitzer to the Program Manager in order to identify key areas needing improvement for the anticipated service life extension. Based on the previous work SMS performed for the USMC Logistic branch, the support team approached RIT for data analysis and engineering assistance with this project.

Approach:
The National Center for Remanufacturing and Resource Recovery (NCR^3) at Rochester Institute of Technology is proposed a four phase sustainment study for the M198 Howitzer. The SMS study supported the Marine Corps System Command Product support team's efforts to provide specific analysis necessary to assess sustainment options for the M198 Howitzer platform.

NCR^3 divided the project into four phases: Phase One consisted of an analysis of the historical maintenance and parts databases on the M198 Howitzer from the past 5 years. The supplied maintenance databases were formatted and filtered for erroneous or irrelevant data. Phase Two used the available maintenance databases conditioned in Phase One to calculate key RAM metrics and compare to the metrics specified in the Required Operational Capability (ROC) document. Phase Three consisted of analyzing the maintenance databases to identify the top degraders (components) of the platform's performance over the period and identify the specific subsystems failing most often on the Howitzer. Phase Four provided additional analysis of the subsystems selected in Phase Three using Failure Modes Effect Criticality Analysis (FMECA).

Results:
Phase I: The primary source of data used in this project is the Marine Corps Integrated Maintenance Management System (MIMMS). The MIMMS dataset provided from the by MCSC encompassed parts replaced during the Fiscal Year 1998 through and including 2nd Quarter Fiscal Year 2003. The original MIMMS dataset was composed of 30,957 records of data. A review of the data quickly revealed that many of the parts in these records were not used on the M198 Howitzer, (for example, Diesel Engines, Radios). Removal of all irrelevant data was accomplished by comparing an accurate list of howitzer related parts against the MIMMS. However, a complete database representing

all of the parts used in the M198 Howitzer was not readily available. NCR[3] created a master list of Howitzer parts using the following documents: USMC Item Application File, US Army Howitzer parts list and the Marine Corps Technical Manuals 08198A-34P/4. All of the parts were combined into a "Boss" file, which contained 2,464 unique National Stock Numbers (NSN). The Boss list was provided to MCSC to do a quality check against internal documents and approved for the purposes of this study.
The 30,957 records contained in the MIMMS dataset contained 1,640 unique parts. The NSNs for these parts were entered into batch files using the Defense Logistic Agency's Fed LOG software. The output of the batch file provided current pricing for each part. 1,191 of the 1,640 parts matched the Boss list.

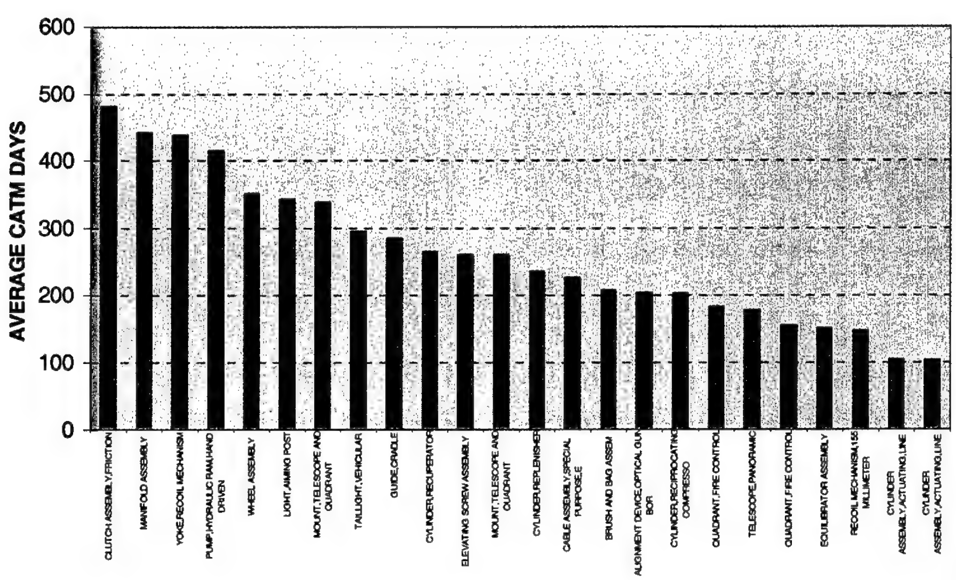
Phase II: A review of the Department of the Army Approved Material Need (Engineering Development) (MN(ED)) for a 155mm Howitzer, 22 May 1972 document provided the specified RAM metrics for the M198.

The MIMMS data were conditioned further in this phase to consolidate each of the multiple records that constitute a single maintenance event into a single record. The resulting database was used to calculate several RAM metrics.

The specified reliability metrics were in terms of "rounds fired" and maintainability metrics were specified in hours. The MIMMS data did not provide that level of resolution so direct comparisons were not possible. The results of the RAM metric analysis did not show any significant degradation over the period examined. Data artifacts and limitations were highlighted.

Phase III: In Phase III, the specific parts that were associated with the maintenance events that resulted in the greatest downtime were identified. The parts were then linked

M198 HOWITZER
PARTS ACCOUNTING FOR GREATEST DOWNTIME
PARETO BY DOWNTIME



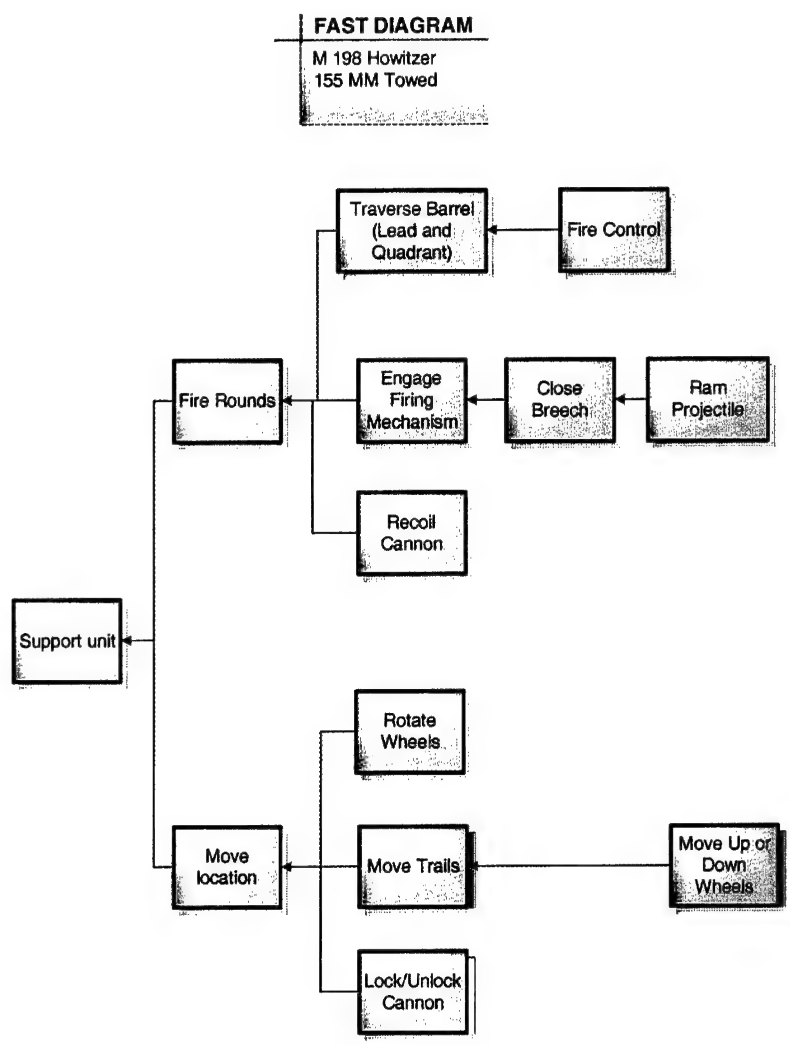
MT18

to the higher-level subsystems. The subsystems identified comprise the top degraders. Additionally, the quantity of parts ordered over the period of interest was calculated from the raw data. Using current pricing, the parts that account for the highest cost and highest replacement frequency were reported.

Phase IV: A Failure Mode Effect and Criticality Analysis (FMECA) was conducted on the subsystems identified through the performance of a Fast diagram. A Functional Analysis System Technique (FAST) diagram was implemented in this study to quickly derive the criticality of primary subsystems to the overall function of the Howitzer. The Fast diagram was then balanced against the top degrader output from Phase Three.

The Failure Mode Effect and Criticality Analysis examined the subsystem and their individual components against a scale of 1 to 10 in the areas of Detection, Severity, and Frequency. By multiplying the scores for Detection, Severity and Frequency, an aggregate rating is achieved. The resulting scores are such that the higher the aggregate grade the more critical the part was on the overall function of the Howitzer.

The study concluded that each subsystem had some specific components that tended to contribute more significantly to the success and or failure of the Howitzer platform. The particular subsystem components were highlighted as an outcome of the study.



Project Title: Remanufacturing the Propeller (LAV Strut and Control Arm) Shaft

Problem:
LAV Propeller shafts are scrapped at the depot during the IRON (Individual Replace Only as Necessary) process when there is coating delamination or rust under the coating. Currently, the Albany, Ga. depot is scrapping 85 percent of propeller shafts (405) from the Light Armor Vehicles (LAV) going through the IRON process. Examples of propeller shafts that have been scrapped are contained in Figure 1.

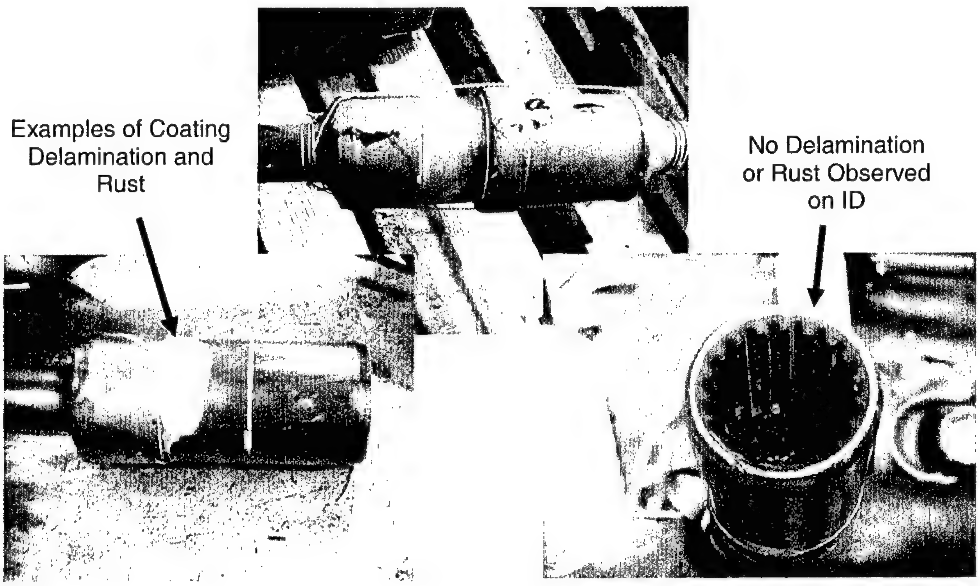


Figure 1. Examples of Propeller Shafts Scrapped at the Albany Depot

Approach:
The Albany depot has requested that NCR[3] develop a remanufacturing process for these propellers shafts. The requirements for this remanufacturing process were:

1. Process could not cost more than 65 percent of the cost of a new propeller shaft,
2. The U-joints could not be removed, requiring that a remanufacturing process be developed that would not damage the U-joints
3. The corrosion and abrasion resistance of the remanufactured propeller shaft needs to be equal or better than the original coating, and
4. Since the coating is a sealing surface, the thickness of the remanufactured propeller shaft coating cannot vary from original coating thickness and it needs to have a similar surface finish and waviness as the original coating.

Results:

Root Cause Failure Analysis

The root cause failure analysis showed that the coating delamination was always observed around the ridge (Figure 2). Failure occurred in this location because the way these shafts were machined left a gap between the coating and shaft. Water was able to seep beneath the coating at this location causing the delamination and rusting.

Recommended Remanufacturing Process

The following remanufacturing process was proposed for the LAV propeller shafts:

- Inspect propeller shafts,
- Remove nylon 11 Coating on OD by single point turning,
- Prepare surface for flame spraying
- Flame spray Absite coating to OD to desired thickness
- Machine Absite coating to proper thickness and surface finish
- Final Inspection

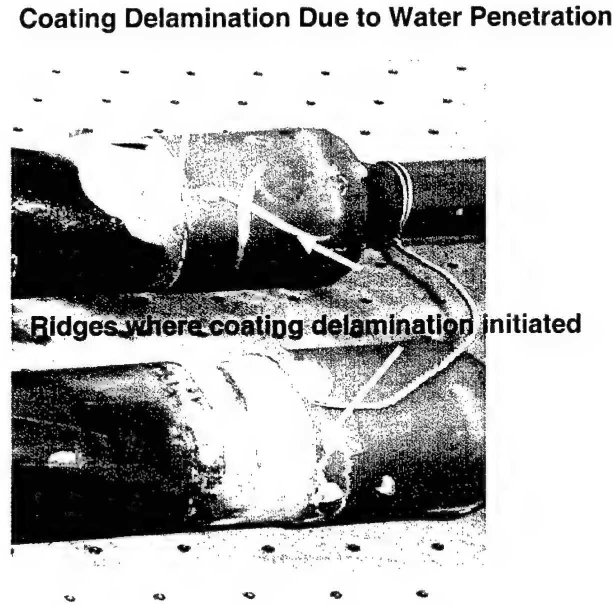


Figure 2. Examples of Coating Delamination

The Absite coating was selected because it has very similar physical and mechanical properties as the original nylon 11 coating and can be flame sprayed to the shaft at temperatures that would not damage the U joints or coating on the ID.

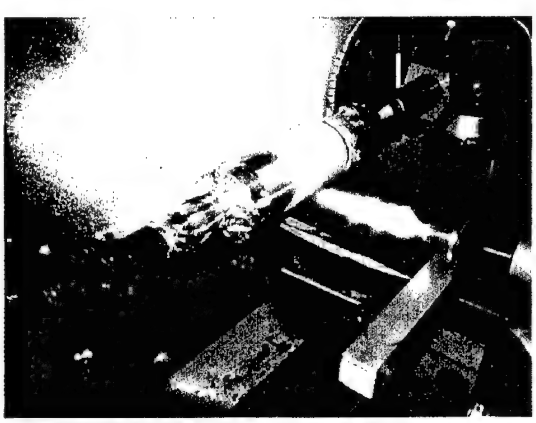


Figure 3. Applying the Absite Coating

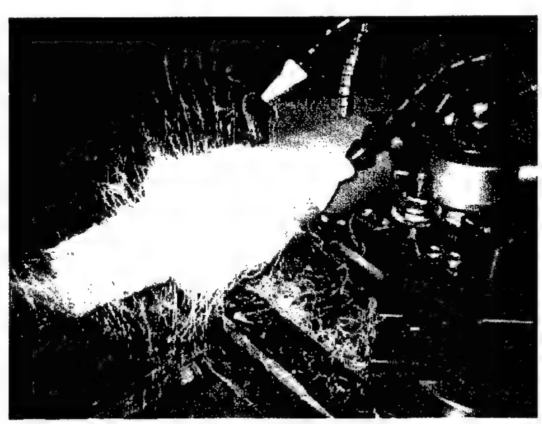
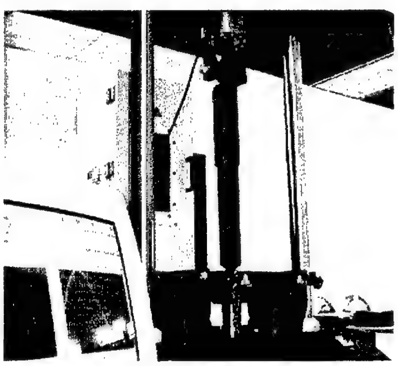
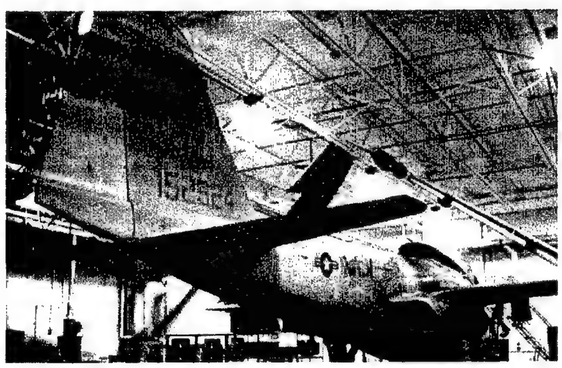
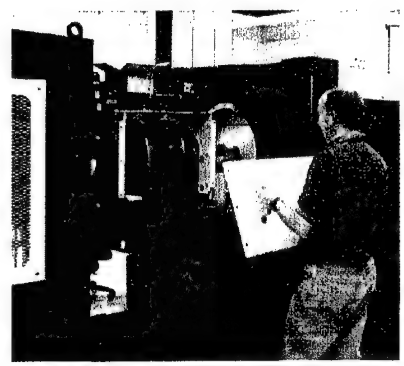


Figure 4. Machining to Final Diameter

Material Aging







Best Available Copy

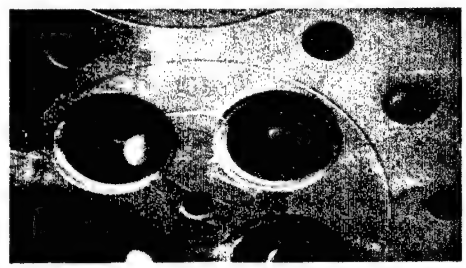
Program 2: Material Aging

Material aging is a process that over time changes the physical appearance, dimensions, or physical or mechanical properties of a component and is the principal cause for the reduction of reliability and margin of safety for engineering systems. When components are placed into service they begin to "age" because of exposure to an environment such as elevated temperature, ultraviolet radiation, moisture, impact, or sliding. Examples of material aging are corrosion, fatigue, wear, fracture, or combinations of these symptoms.

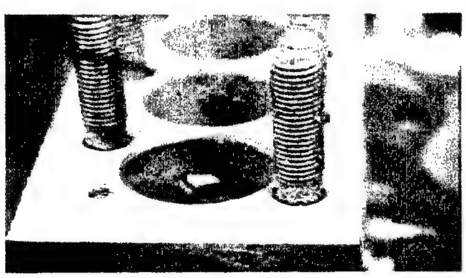
Figure 1 Material Aging Examples

Fracture

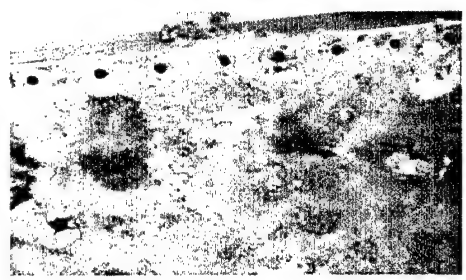
Fatigue



Wear



Corrosion



Understanding material aging is the key to gaining an insight into part and equipment failures. This technology contributes to the advances in the application of tools and methods that can predict equipment's future maintenance needs and remaining useful life. Understanding material aging is also the key to effectively and reliably extending the life of aging assets and is a cost-effective means to keep equipment operating longer and more reliably.

Table1 shows the capabilities and enabling technologies developed to support the Material Aging Program. The awareness of which material aging mechanism is present is the first step of any life extension program.

Table 1 Material Aging Capabilities and Enabling Technologies

Capabilities	Enabling Technologies
Structural Health Monitoring (Condition Assessment)	Damage Detection (Nondestructive Inspection)
Material Based Prognostics	Structural/Analytical Analysis
Restoration	Signature Analysis
	Root Cause Failure Analysis
	Fault Propagation (for Predictive Models)

The material aging capabilities include:

- Structural health monitoring or condition assessment,
- Material based prognostics, and
- Restoration.

Condition assessment understands which material aging mechanism is present and the extent to which the aging has affected the function and physical and mechanical properties of the component.

The ability to predict the time to failure, on a real time basis, benefits asset health management systems and has the potential for reducing the overall life cycle costs. RIT is using material based prognostics to generate predictive models using simulated laboratory testing and fault propagation. This prognostic development begins by using individual components and is then verified using subscale or full scale systems.

Material based prognostics determine the remaining life of a component that has undergone material aging. Typical material based prognostics involve simulating the material aging mechanism in the laboratory and then running components or simulated components to failure. Signature analysis techniques and embedded sensors are used to monitor the material aging mechanism and determine the remaining life of the component.

Signature analysis is concerned with the analysis of signals obtained from subassemblies or components. It is a diagnostic technique where certain parameters from a set of characteristic signals are extracted from a particular device that could provide useful information about the "state of health" of the device. An example of extracted parameter or "feature" might be the spectral density signal show in Figure 2. This figure shows that as the condition of the component degrades under a particular fault, the feature changes in a predictable manner. The previously mentioned "state of health" is a measure of the type and severity of degradation the device has experienced thus far in its life and is a crucial piece of information in gauging the potential for remanufacturing. Thus, signature

analysis techniques can be used to determine the amount of material aging or the type of material aging occurring in a component.

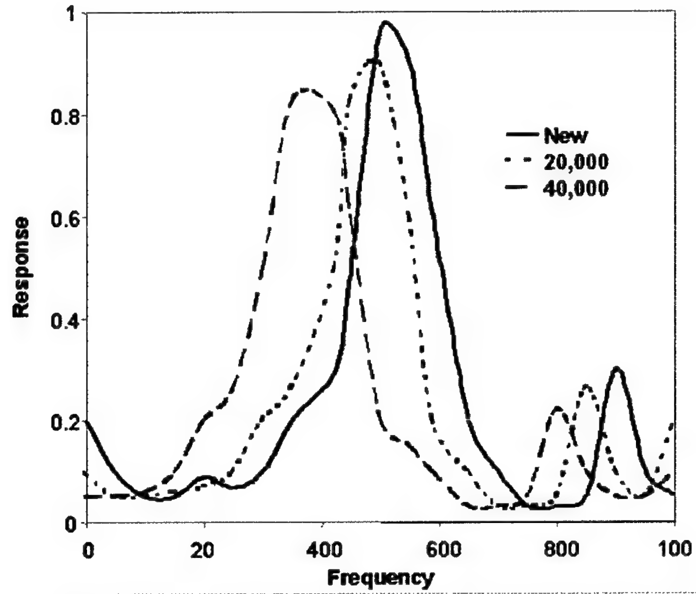


Figure 2. Change in a Feature with Aging

Restoration brings back a component that has been in service back to a pristine, like-new condition. After a root cause failure analysis has identified the material aging mechanism, a restoration technique is selected. Understanding of how the component failed enables a restoration technique to be selected that will improve the performance of the restored or remanufactured component by providing increased resistance to the material aging mechanism. If the material aging mechanism is corrosion, the material applied to restore the component can be selected to have improved corrosion resistance over the original material.

Root cause failure analysis uses optical and scanning electron microscopy techniques to determine changes in a components physical appearance and microstructure. In addition, physical property measurements such as hardness and tensile are made to determine the effect of the material aging on the reliability and functionality of the component. Once the root cause failure analysis has identified the material aging mechanism, a restoration technique can be developed for the component, or design changes can be recommended to increase its useful life.

Figure 3. Understanding Material Aging
Supports the Development of Material Restoration Techniques

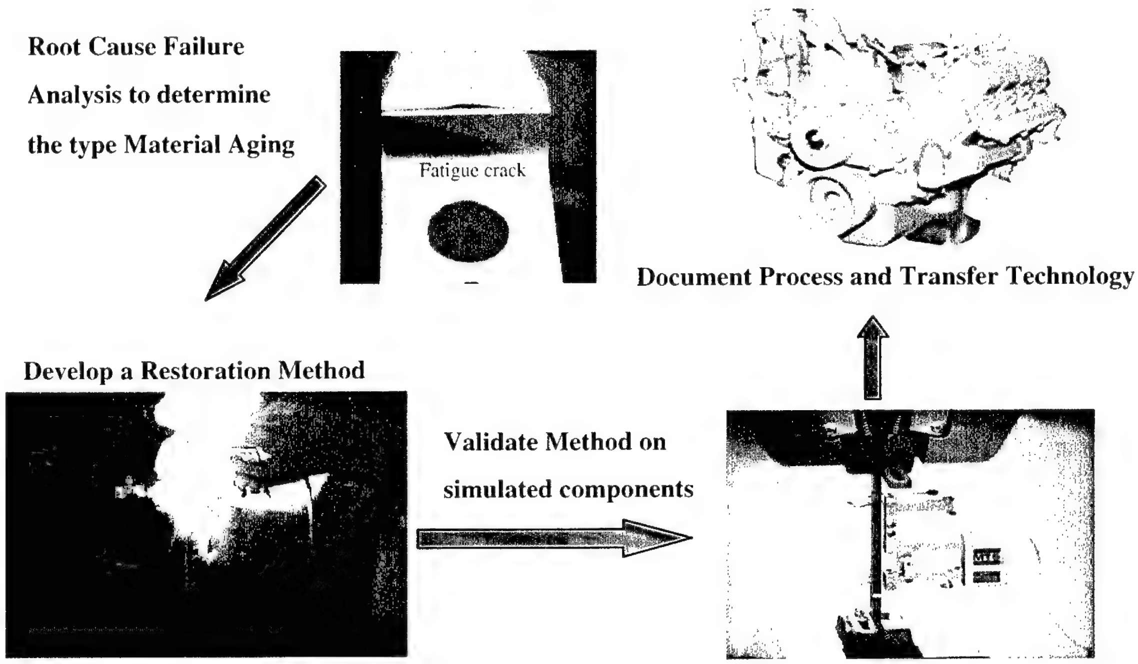


Figure 4 shows how the technology developed within the Material Aging program is enhancing its capabilities and supporting the other DoD programs. The Material Aging program focused on understanding material aging and applying this knowledge to structural health monitoring, component restoration, and material based prognostics. The technologies developed include **finite element analysis for structural modeling** (Advanced Hull Form and Westfoil Structural Design) fatigue life prediction (EA-6B Hydraulic Actuator), applying **signature analysis techniques** (Signature Analysis and Prognostic Development for LAV Planetary), **root cause failure analysis** (Prognostic Development for LAV Planetary, EA-6B Hydraulic Actuator) and **solid modeling** (Westfoil Structural Design, EA-6B Hydraulic Actuator and EA-6B Turtleback Remanufacturing).

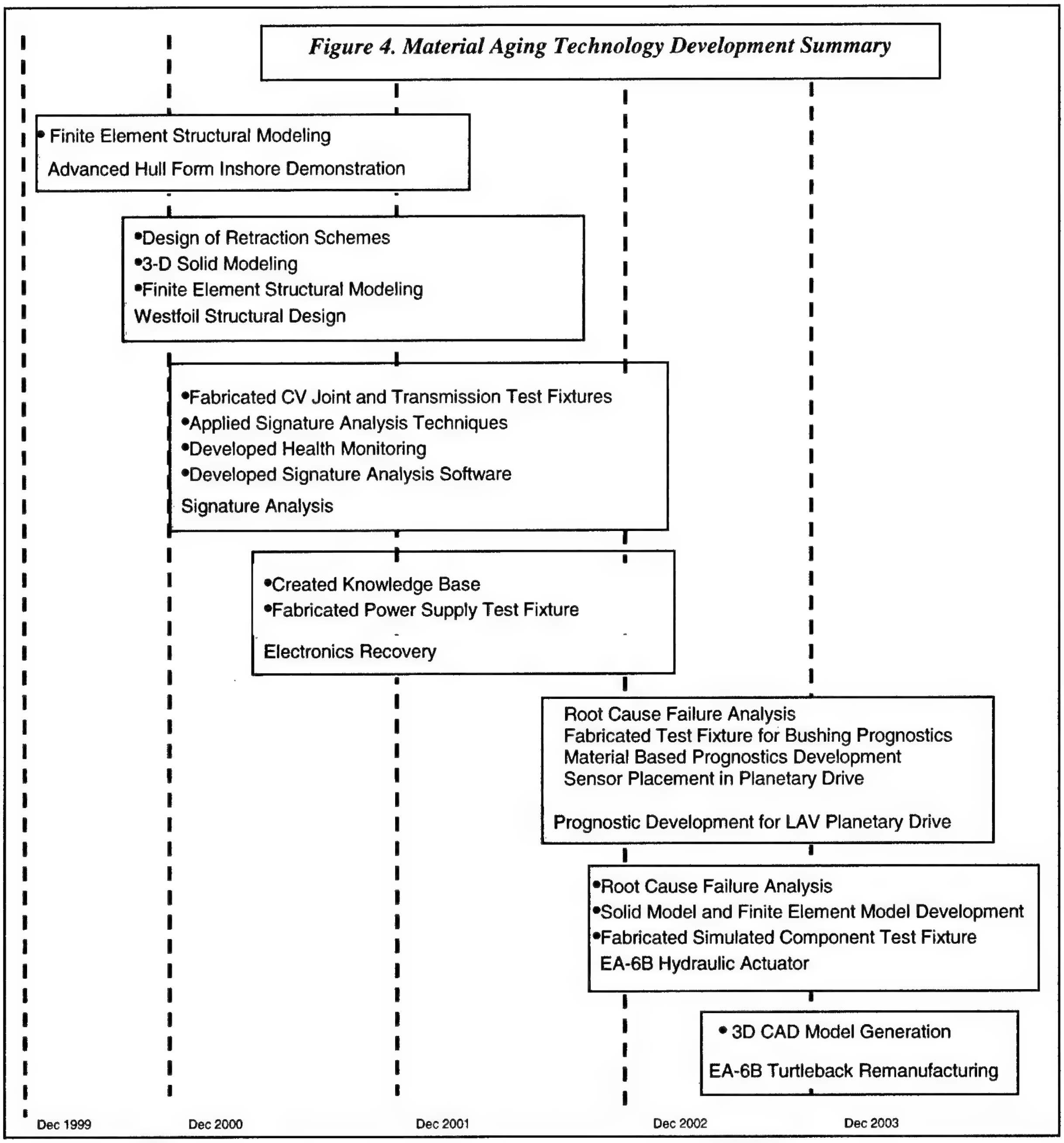


Figure 4. Material Aging Technology Development Summary

The primary projects that were conducted under the Material Aging program included:

- Advance Hull Form Inshore Demonstrator study — Sponsor / ONR - Navatek
- Westfoil Structural Design Analysis — Sponsor / ONR - Navatek
- Signature Analysis — Sponsor / ONR
- Electronic Recovery — Sponsor / ONR
- Development of Prognostic Technology for LAV Planetary Drive System — Sponsor / PM-LAV Office USMC
- EA-6B Flaperon Actuator — Sponsor / NAVAIRSYSCOM
- EA-6B "Turtle-back" Manufacturing Cost study — Sponsor / NAVAIRSYSCOM

Material Aging

PROJECTS

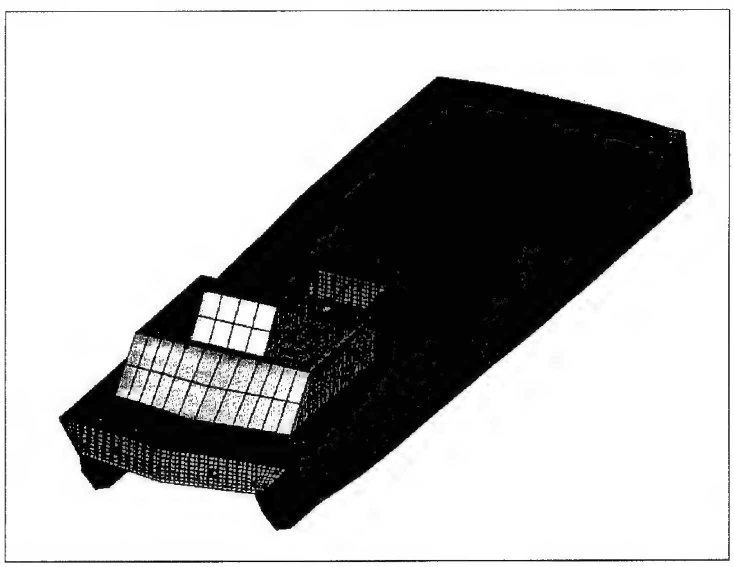
Project Title: Advanced Hull Form Inshore Demonstrator Study

Problem:
The Advanced Hull Form Inshore Demonstrator (AHFID) study, under the direction of the Office of Naval Research, was a project to develop and demonstrate an azmuthing podded propulsor. The test platform to be used in the demonstration of this technology was the remanufactured and converted SES200.

In performing the SES200 remanufacturing assessment and analysis, NCR^3 amassed considerable data and knowledge regarding the configuration and structural integrity of the SES200 which was incorporated in the SES200 information database. NCR^3 was tasked with maintaining configuration control of the SES200 throughout both the remanufacturing and AHFID programs, and serving as structural analysis consultants as needed.

Approach:
The maintenance and development issues related to the SES200 information database is more completely described in the LEEDS project description and as such will not be repeated in this section.

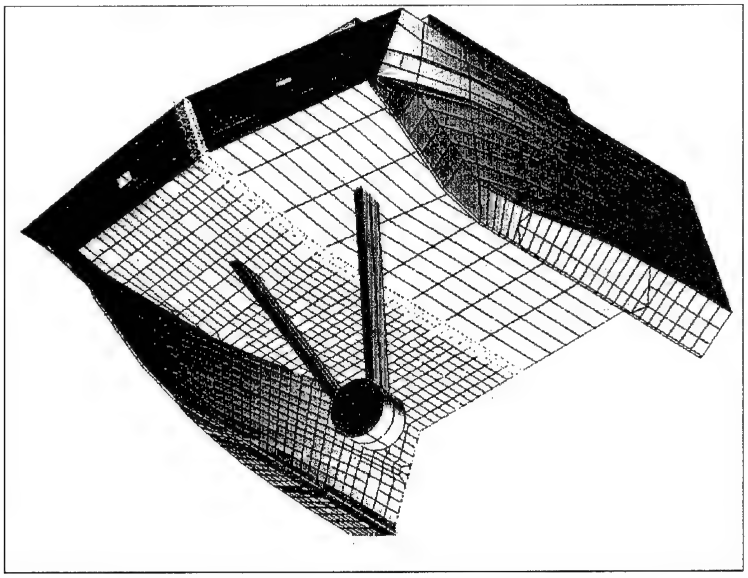
In support of the SES200 remanufacturing assessment, NCR^3 developed finite element structural models which were made available for use in ongoing configuration investigations. AHFID propulsor structural information was incorporated into SES200 structural models and analyses were performed to evaluate the structural integrity of the vessel at the interface location.



Base FEA Model

Results:

Structural results pertaining to the relative stiffness of the vessel/propulsor interface were given to the AHFID Project Team to be used in dynamic analyses of the propulsor.



FEA Model Indicating AHFID Propulsor Location

In 2002, NCR[3] was informed by ONR that the reconfigured SES200 would not be used as the test platform for the AHFID program resulting in NCR[3] support for the program being discontinued.

Project Title: Westfoil Project

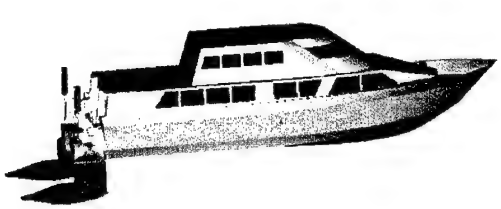
Problem:
NCR[3] demonstrated through the SES200 project the vast benefits of a rigorous remanufacturing assessment process and developed tool sets which can be applied to a broad array of systems (LEEDS). To further demonstrate LEEDS and expand the application of the tool sets to include design and conversion, NCR[3] collaborated, under the direction of the Office of Naval Research, with Navatek Ships LTD in the undertaking of the Westfoil Project.

The Westfoil is an 80ft vessel which initially had rotationally retractable hydrofoils located both forward and. The intent of the Office of Naval Research was to convert the vessel from a hydrofoil to one that incorporated advanced lifting bodies which would also retract. To assist in this effort, NCR3 was tasked with applying the LEEDS process to the conversion design, developing a conceptual design for the retraction mechanism, performing finite element analysis of the advanced lifting bodies, and exhibiting configuration control of the vessel and systems through the creation and population of a vessel database.

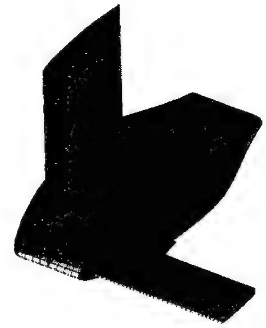
Approach:
To address the project goals, the project tasks were divided into four main groupings: Feasibility Study, Retraction Mechanism Design, Finite Element Analysis, and Westfoil Database.

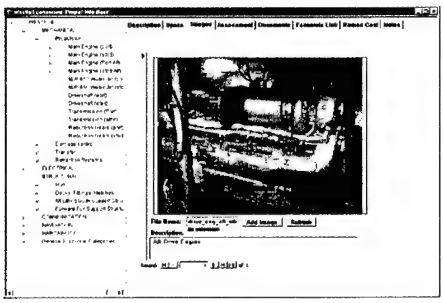
Feasibility Study:
The first phase in a remanufacturing or conversion project is a feasibility assessment to determine best remanufacturing and conversion options. The tools and methodology applied to the Westfoil project were based on those developed for the SES200 project and included such activities as Data Collection, Function Analysis, Condition Assessment, Failure Mode Effects and Criticality Analysis (FMECA), and Reconfiguration Options Assessment.

Retraction Mechanism Design:
A conceptual design was pursued for the best configuration as determined by the feasibility study and in accordance with the proposed operational specifications. To resolve any interference issues with the proposed design, a 3D solid model of the vessel and retraction mechanism was constructed.



Finite Element Analysis:
To insure the structural integrity of the lifting body assembly, Finite Element Analysis (FEA) was used to perform a structural analysis. Results of the analysis were used to propose materials of construction and internal structural configuration.

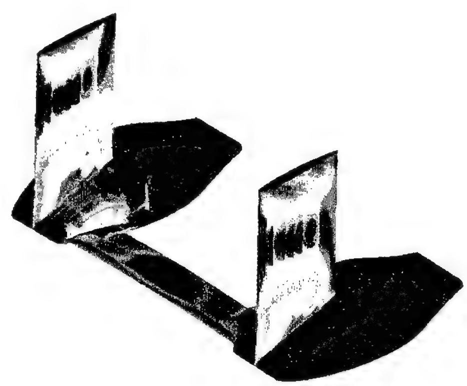




Westfoil Database:
To preserve and capture configuration and design information and maintain a living history of the vessel, an information database was constructed. The information contained within database included all data captured and generated as a result of the feasibility studies, design effort, and structural analysis effort.

Results:
The results of this project indicated that the remanufacturing and conversion process (LEEDS) can be tailored to suit design projects.

- Feasibility studies identified the strengths and weaknesses of several different retraction schemes leading to a ranking of the design options.
- Conceptual design of the highest ranking retraction option was performed and dimensional integrity was confirmed with 3D Solid Modeling.
- Structural analysis of the lifting bodies was performed using Finite Element techniques.
- An information database was constructed and populated to serve as a configuration management tool and historical record as the configuration of this vessel evolves.



Project Title: Signature Analysis Initiative

Problem:

The purpose of this initiative was to apply and expand the use of signature analysis as a non-destructive diagnostic method for assessing the type and extent of material aging defects in machinery. The proper assessment of material aging defects is crucial to being able to determine the state of health of equipment. Two NCR[3] projects that supported this initiative are as follows.

CV Joint Testing

The first project involved the development of diagnostic algorithms to assess the quality of remanufactured automotive constant velocity (CV) joints. This work was performed in conjunction with the development of a CV joint test fixture as a technology demonstration for the remanufacturing industry. In addition to algorithm development, software tools were developed that facilitated the acquisition and processing of data for diagnostic assessment.

Transmission Testing

The second project consisted of test fixture and algorithm development to assess the state of health of a manual automotive transmission. The primary goal of the project was to use the algorithms and diagnostic techniques learned in the CV joint project as a basis and expand that diagnostic set to include other methods. Other objectives of this project were to develop a computer interface with data collection and data processing capabilities and to demonstrate repeatability of measurements through multiple rebuilds with the same components. Specific areas which were targeted for diagnostic assessment were the detection of surface defects on the gears, and quantification of misalignment of drive components.

Approach:

A. *CV Joint Testing*

A series of tests were run on a collection of CV joints in good condition and on joints with documented known defects with varying levels of severity. This was done to understand how the joints behaved with respect to vibration signature and to determine which diagnostic parameters react to defects in CV joints. An overview of the basic test procedure was as follows:

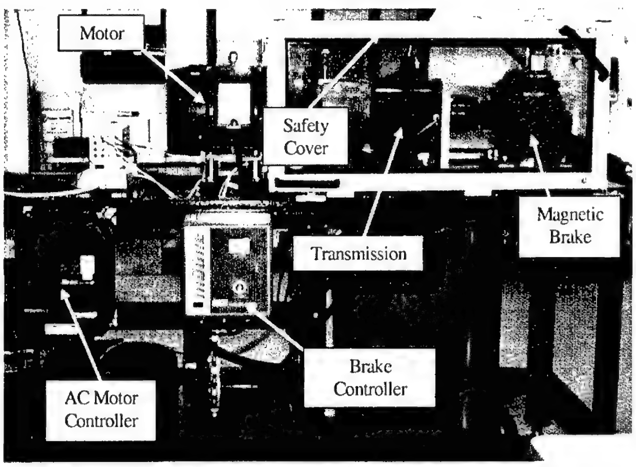
- Captured signature data on a variety of CV joints for evaluation and comparison.
- Verified repeatability of test results.
- Validated signature analysis methods for determining if a joint does or does not have a defect.
- Determined which diagnostic parameters properly indicated CV joint quality.

After selection of the appropriate diagnostic algorithms, further testing was performed using a master joint to characterize defects while varying only one component at a time. The master joint was disassembled and reassembled multiple times introducing one new component each time with varying degrees of defect. Master joint testing was performed varying the following components:

- Worn ball cages
- Varying outer race (bell housing) clearance
- Worn inner races

B. Transmission Testing

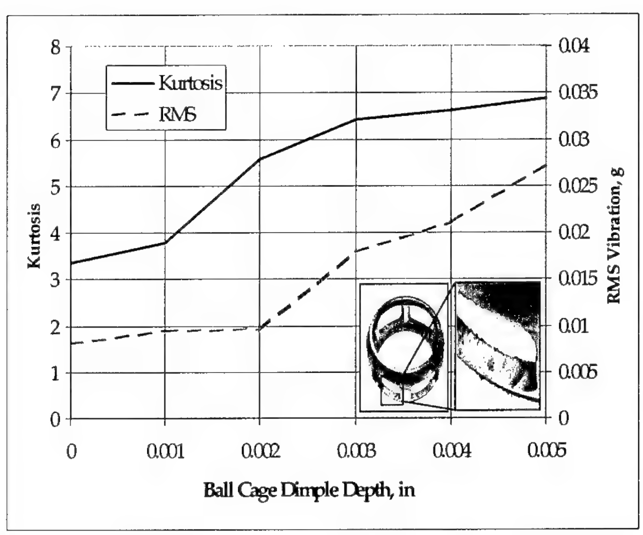
To apply signature analysis techniques to the transmission, a test fixture was developed which consisted of a drive motor, support base, brake, and data acquisition system. Vibration data was acquired at several locations on the transmission for all four gearing scenarios (1st, 2nd, 3rd and Reverse). Gears with varying levels of defects were installed in the system to test the ability of the diagnostic algorithms to detect those defects. A software program was created to analyze data according to various gear fault sensitive methods as well as trend data and compare multiple configurations. In addition to gear fault detection, an attempt was made to quantify the effects of system misalignment on diagnostic measures.



Results:

A. CV Joint Testing

The CV Joint Testing demonstrated the ability to distinguish between good and defective automotive CV joints. Software routines were developed to facilitate the capture of vibration signature data and the processing of that data using statistical analysis methods. The diagnostics demonstrated the ability to indicate the relative extent of CV joint wear as compared to threshold values established through baseline testing. Validation of the tester and



Best Available Copy

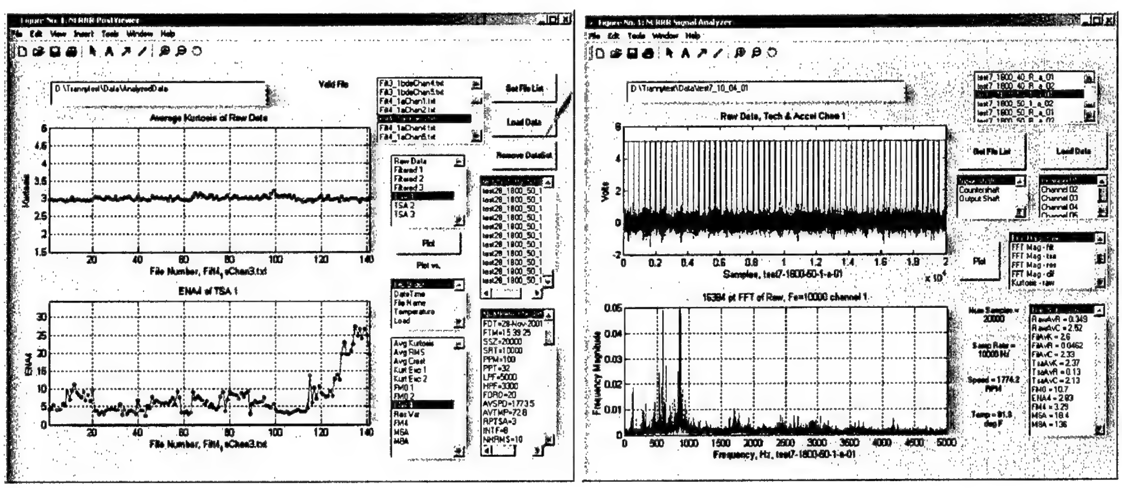
diagnostic methods was confirmed by successful field testing of the unit at a CV joint remanufacturer. The tester consistently demonstrated the ability to differentiate between acceptable and unacceptable remanufactured CV joints.

B. Transmission Testing

Results of the transmission test program indicate some of the diagnostic algorithms were successful at detecting gear damage at elevated damage levels. However, in most cases minor damage was not detected by the diagnostic algorithms. The final conclusion of the investigation was that the test fixture did not have sufficient capacity to adequately load the transmission and that future geared system testing would require the ability to nearly fully load or overload the gears being studied. In effect, most of the test results were more indicative of the quality of the rebuild of the transmission when new test gears were introduced into the system.

Due to the low level of loading attainable by the tester, the effects of disassembly and reassembly had a disproportionate impact on fault detection and measurement. Some of this was partially accounted for in the misalignment studies. The results of the misalignment study indicated that misalignment can have an effect on diagnostic readings and can be quantified when misalignment can be controlled. Control and repeatability of misalignment was demonstrated at the "brake-end" of the system. However there was inability to perform meaningful misalignment study on the input end due to the lateral "float" of the transmission input shaft.

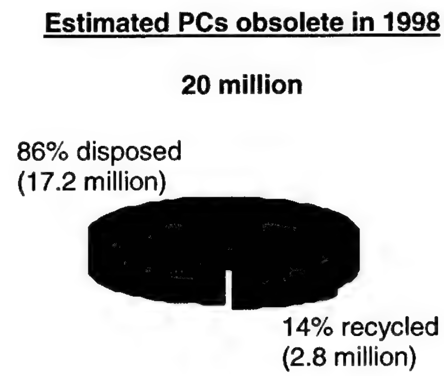
The signature analysis software tool developed in conjunction with the transmission testing demonstrated the ability to assess individual signals, compare multiple signals, and trend diagnostic measures over time. It was designed with the flexibility to be used on subsequent programs that require signature analysis capabilities.

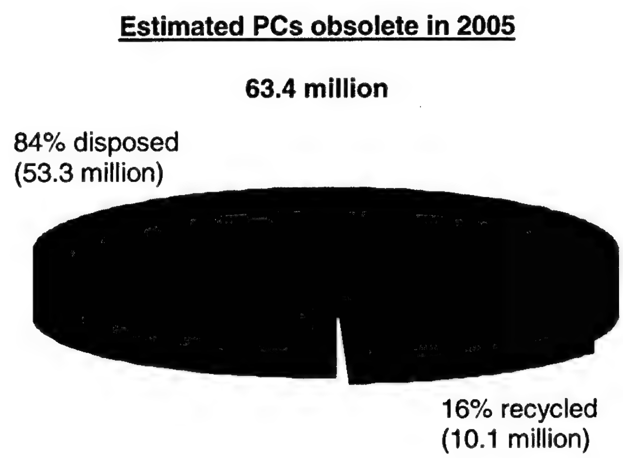


Signature Analysis Software Tool

Project Title: Electronics Recovery

Problem:
The disposal of electronics is a growing concern, and its future remains uncertain. State and municipal legislation are restricting disposal of electronics in landfills because of high volume and hazardous waste concerns.





A recent report entitled *Electronic Product Recovery and Recycling Baseline Report: Recycling of Selected Electronic Products in the United States* from the National Safety Council (NSC), estimates that 20 million PCs became obsolete in 1998 and only 14 percent were recycled or donated. In 1999, 24 million PCs became obsolete, but only 11 percent were recycled. Even though the total number of recycled computers is expected to rise annually, NSC expects that by 2005 the recycling industry will process only 16 percent of the nation's 63.4 million obsolete computers.

The predicted inability of the recycling industry to handle the volume of obsolete PCs in 2005 illustrates the need for efficient computer and electronic recovery operations. Although technologies will continue to be developed for electronics recycling, higher forms of recovery (namely remanufacture and reuse) have been left largely unchallenged.

NCR[3] is investigating the feasibility of electronics remanufacture and reuse in today's business environment. It is clear that factors such as the rapid rate of technology advancement, product diversity, and other logistics issues seriously complicate the development of a cost-effective business model. However, the benefits of merely understanding these limiting factors can result in the creation of electronics design guidelines to overcome recovery constraints and enable the remanufacture and reuse of electronics in the future.

The objective of this project is to investigate the feasibility of recovering electronics for remanufacture and reuse.

Approach:
From knowledge gained from an investigation into the feasibility of electronics remanufacturing and reuse, SMS will design metrics to guide the manufacture of future electronics for advanced recovery methods at end of life.

SMS will first assess the current state of technology used to recover electronics and investigate the critical variables that influence feasibility of electronics recovery. Next, a feasibility study will be conducted on a representative family of electronic products and a business case for its remanufacture and reuse will be constructed. The last phase will be the development of design guidelines that will help future recovery of electronics by optimizing cost-efficient methods of remanufacture and reuse.

Results:
SMS has developed an extensive knowledge base of research white papers and industry statistics. This knowledgebase covers areas of materials within consumer electronics, current reuse/recycle implementations, and legislative issues. This dataset was obtained from a wide range of academic, government, and commercial sources.

The project also investigated a component within a computer for a feasibility study. The component was a power supply and signature analysis techniques were applied to determine if the power supply was able to be reused for an additional lifecycle. The results of this testing were promising. However, additional testing is required to quantify these initial promising results.

Project Title: Development of Prognostic Technology for LAV Planetary Drive Systems

Problem:

The LAV planetary drive system has a recurring problem with overheating. If overheating is allowed to continue, severe damage to the drive system occurs. Each of the eight wheels on an LAV contains a planetary drive. There is currently no easy way to check for drive overheating other than stopping the vehicle and touching each hub to monitor the drive temperatures.

Approach:

The problem with the planetary system was approached at four levels.

1. The sixteen planetary drives from two LAV's were disassembled and examined for wear or other damage to the components. Also, a failed planetary gear system was obtained from the Nevada proving grounds and was extensively analyzed to determine the root cause of failure.
2. A bench top tester was designed and built to gather temperature and life data on the bushings used in the planetary gear system.
3. A dynamometer was installed along with fixturing for testing two planetary systems at once. Each planetary system was equipped with multiple temperature and vibration sensors.
4. Sensoring a LAV's with thermocouples in the planetary drives for real time temperature monitoring.

Results:

The inspection of the sixteen LAV drives showed that the LAV that had not been "Inspect and Replace Only as Needed" (IRONed) had obvious wear on the pinions, which serve as the axles for the planetary gears in the drive system. The corresponding planetary gear bushings had large amounts of metal debris embedded in them but were not significantly worn. The LAV that had already been IRONed had no signs of bushing or pinion wear.

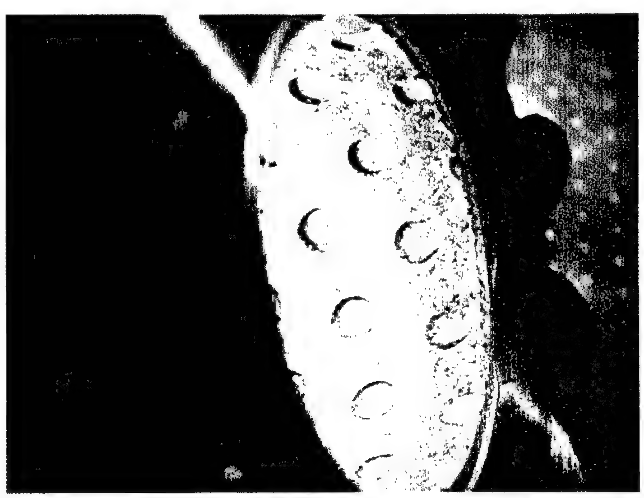


Figure 1. Bushing Containing Metal Debris

The failed planetary system from the Nevada proving grounds (Figure 2) showed signs of severe overheating; charred oil and discolored steel. The planetary

bushings had no remaining acetal surfaces, and in some cases had no remaining bronze sub surface material. In addition, there was a portion of the steel liner that was extruded from the side of the gear.

The root cause of failure was the loss of an oil seal resulting in loss of oil lubrication to the planetary bushings. The bushings in turn overheated and lost their acetal surface, which caused additional overheating at the bushing-pinion interface. Loss of bushing material caused excessive clearance between the bushings and the pinions resulting in galling and rolling action between the bushings and the pinions. At this stage, the bronze and steel of the bushings started to extrude out the face of the gear. More pinion-gear clearance allowed the planetary gears to grind against the faces of the planetary carrier plate. Finally, most of the planetary components were damaged beyond repair or reuse.

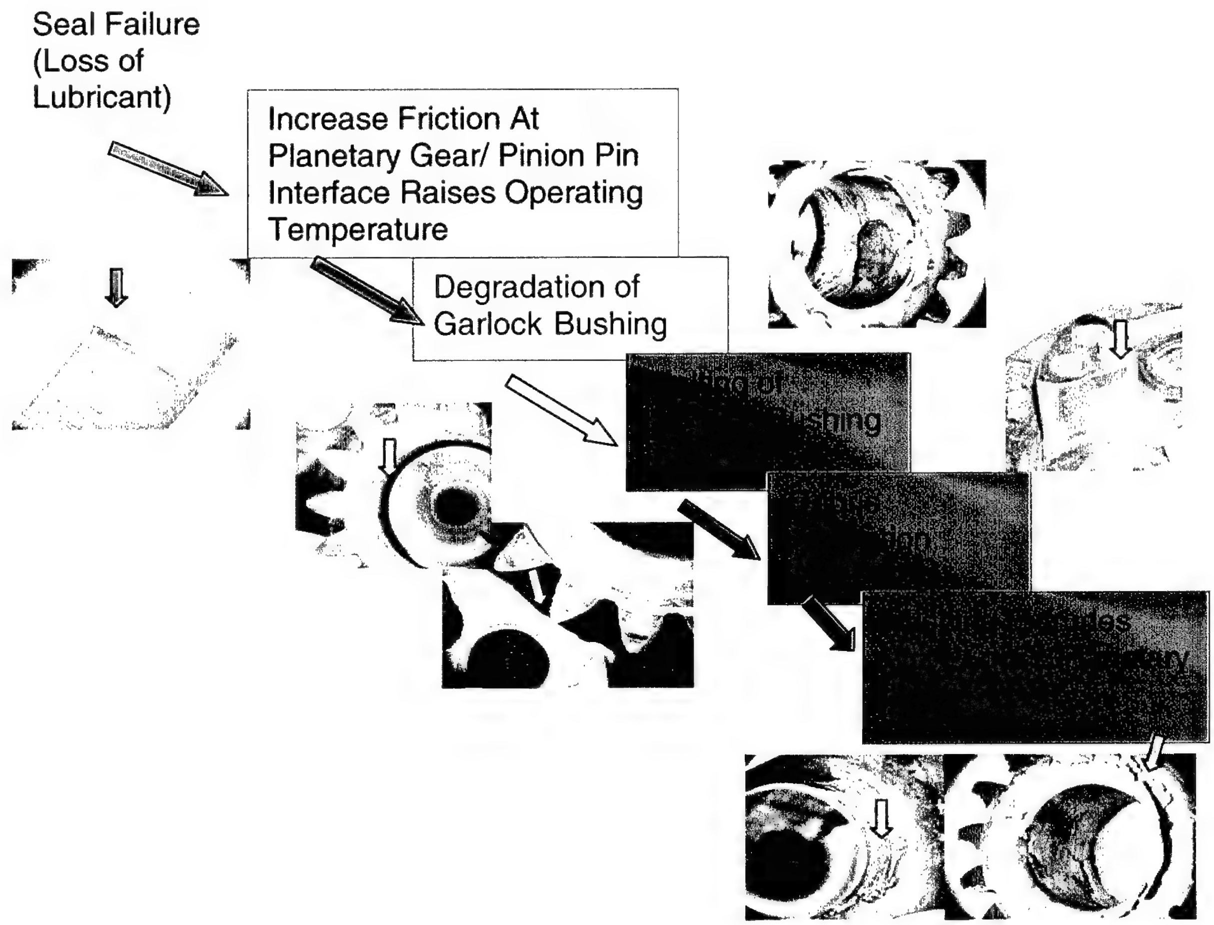


Figure 2. Root Cause Failure Analysis of Failed Planetary Drive

A bench-top bushing tester was designed and built to determine the affect of speeds, temperatures, and loads on planetary bushing life. End of life for a bushing was defined at the point at which the acetal layer was completely worn through to the bronze layer. Once the acetal was gone, the bushing temperature climbed rapidly as the steel pinion ran against the bronze layer. In the actual planetary system, this would be the beginning of severe planetary damage.

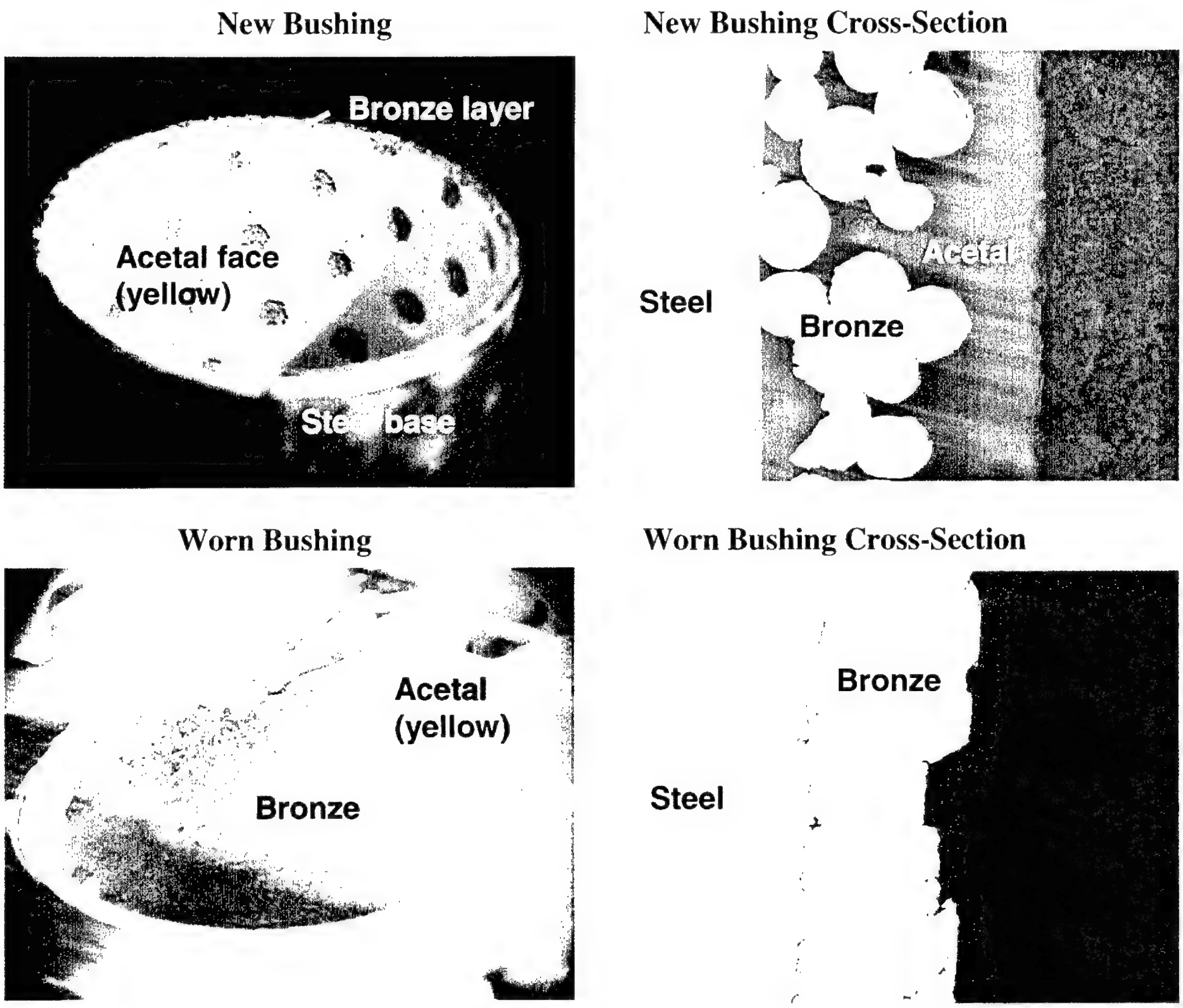


Figure 3. Photomicrographs on New and "Worn" Bushings

The chart below (Figure 4) shows a typical experimental run on the bushing tester. The bushing is rapidly heated by the hot oil to an average temperature of 260° F. As frictional heating between the pinion and bushing occurs, the acetal slowly flows until there is pinion-to-bronze contact. At that point, there is a sudden spike in temperature from 270° F to over 290° F and the test is terminated.

Figure 4. Example of Bushing Temperature vs. Run Time

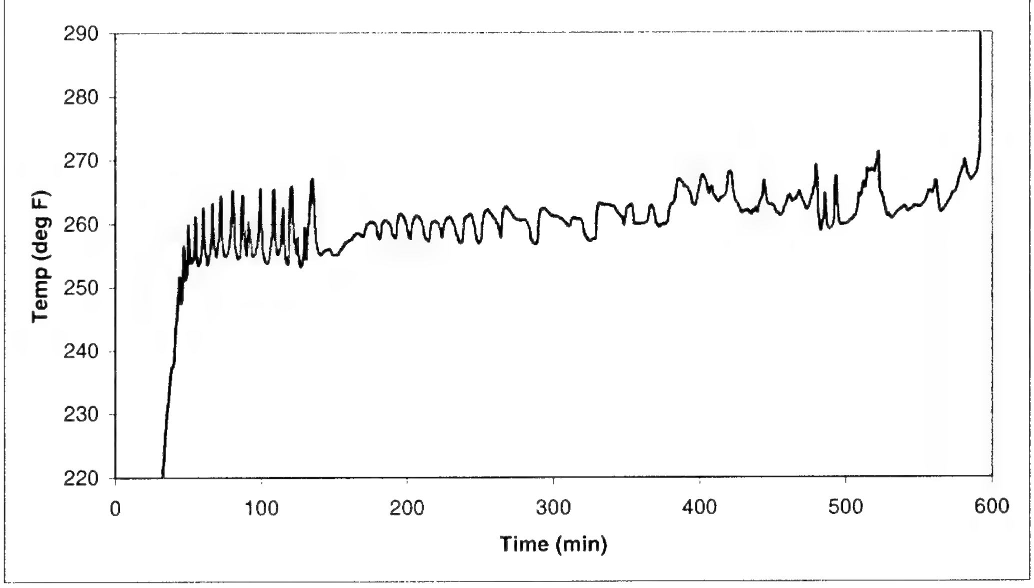
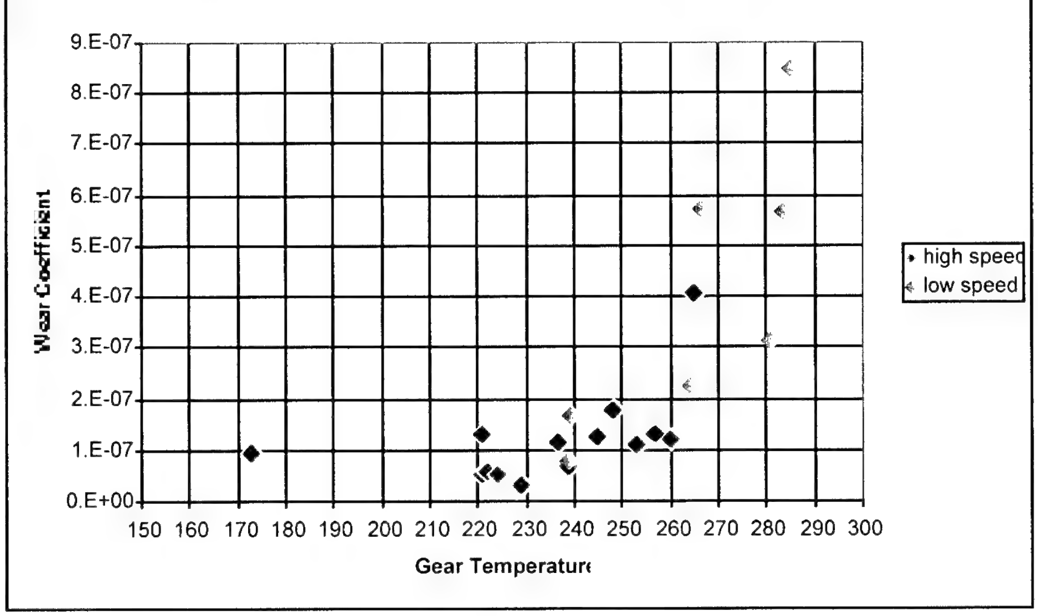


Figure 5 below shows the relationship between bushing wear (wear coefficient) and the temperature of the gear and bushing. As the gear temperature increases, there is an increase in the wear coefficient with a corresponding decrease in the life of the bushing. Above 260° F, there is a dramatic decrease in bushing life regardless of speed.

Figure 5. Effect of Gear Temperature and Speed on Wear Coefficient



System level testing of the complete planetary assembly is accomplished using the dynamometer test stand. The dynamometer enables the planetary to be subjected to speeds and loads similar to those from actual vehicle while in a controlled laboratory environment. Results from component level tests will be validated on the system level

The dynamometer enables off-vehicle, system level testing of the LAV planetary. Programmable test profiles enable the planetary to be subjected to varying speeds and loads within normal vehicle operating conditions. Continuous data acquisition captures changes in readings from embedded sensors. This data will be used to develop prognostics to predict remaining operating life of planetaries on LAVs operating in the field.

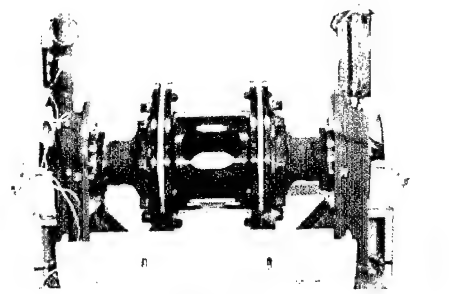


Figure 6:* *Two LAV Planetaries coupled together undergo simultaneous testing

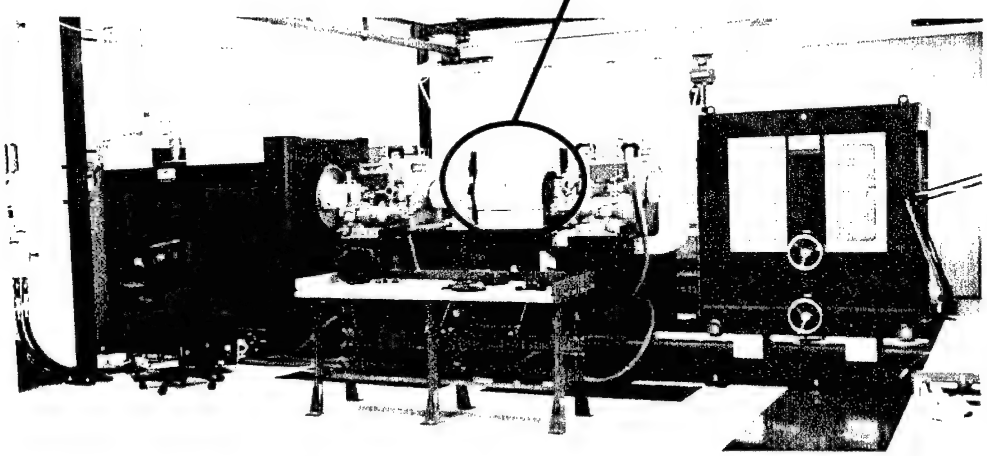
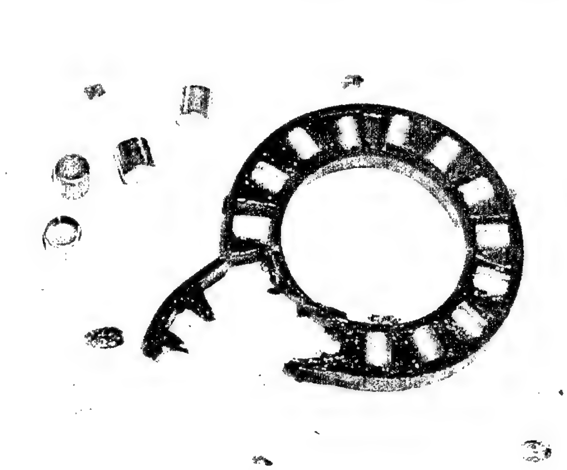


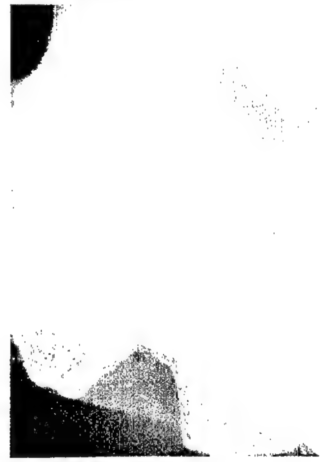
Figure 7: 300 Hp Dynamometer Test Stand

System level testing on the dynamometer has demonstrated several modes of failure that may be attributed to improper planetary set-up. These failures are similar those on vehicles operated in the field and may be remedied by improvements or changes to maintenance procedures.

Figure 8. Failures from Incorrect Shimming



Axial Casing Bearing – Broken Cage, Loose Bearings



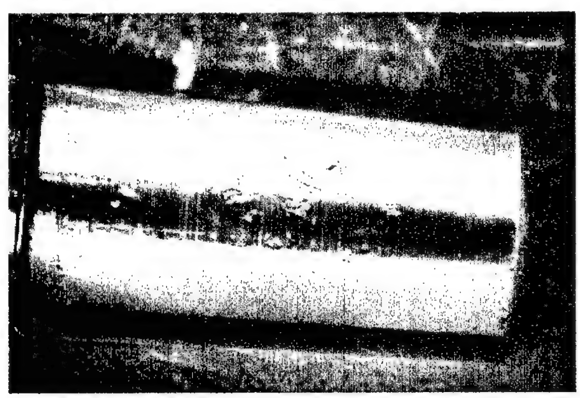
Sun Gear – Pitting in Bearing Contact Surface

Insufficient axial clearance from improper shimming caused high axial bearing loads that resulted in failure of the axial casing bearing and pitting on the contact surface of the sun gear

Figure 9. Bearing Failure from Incorrect Preload

Error!

Inner Bearing Race – Surface Pitting



Tapered Roller Bearing – Surface Damage from Wear Particles

Improper preload on the tapered roller bearing that supports the wheel hub resulted in premature failure of the bearing. Preload was increased by 15 percent over the maximum recommended setting and resulted in fatigue failure of the inner bearing race. The small, sharp fragments of metal from the inner race were dispersed throughout the planetary causing premature wearing of other moving parts.

System level testing has also demonstrated that elevated oil temperatures result in planet gear bushing failure. At elevated temperatures the acetal (yellow plastic) layer begins melt, flow and extrude out the ends of the bushing. This leaves only the bronze layer of bushing to rotate on the pins, causing accelerated wear. Eventually the wearing process caused the pin-to-bushing clearance to increase to a point where the planet gears contact adjacent parts within the planetary and the entire assembly fails.

Figure 10. Bushing Failure from Elevated Oil Temperature

Planet Gear with New Bushing

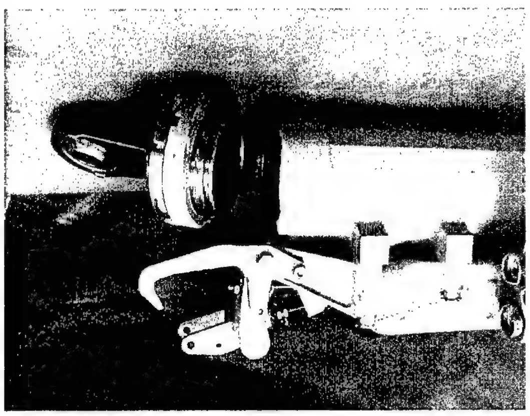
Start of Failure - Acetal Layer Melting

After Failure (shown unrolled) - Acetal Layer Gone, Bronze Layer Exposed

System level prognostics work for the planetary assembly was also begun. Using the dynamometer, time-to-failure rates for the planet gear bushings are being examined under various operating conditions. The rate and magnitude of temperature change during the failure process is also being examined. This data will then be compared to the component level test data and used to develop the algorithms that will predict the time-to-failure rates for the on-vehicle temperature monitoring system.

Project Title: EA-6B Flaperon Actuator Project

Problem:
There have been a number of EA-6B flaperon actuators failures occurring in the aluminum housing within the first three threads on the fixed end of the actuator (Figure 1). Root cause failure analyses showed that the fracture started at the root of the last end cap thread and then progressed along its circumference (60 to 70%) before the catastrophic failure occurred. Thus, this analysis concluded that the cylinders failed due to fatigue. Also, there were no apparent metallurgical defects found in any of the failure regions.



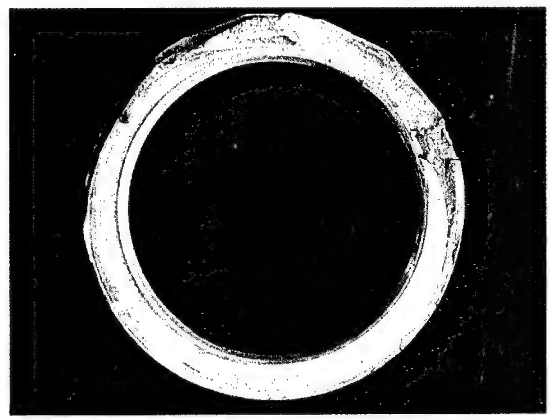


Figure 1: Flaperon Actuator Failures

The flaperon is a manually operated control surface which essentially has the same function as ailerons. The only difference is that they are on the top of the wing and disrupt the smooth airflow over the top of the wing, thereby decreasing lift, and causing the airplane to roll. They are mainly used at slow speeds when conventional ailerons cannot provide enough roll rate.

The flaperon is moved by a dual cylinder hydraulic actuator. This actuator consists of aluminum housing with steel end caps threaded into each end. The aluminum portion of the actuator is painted yellow in Figure 2. The end caps are labeled 2 and 3. The approximate length of this actuator is around 2 feet. The hydraulic fluid inside the aluminum section is at 275°F and a pressure of 3000 psi.

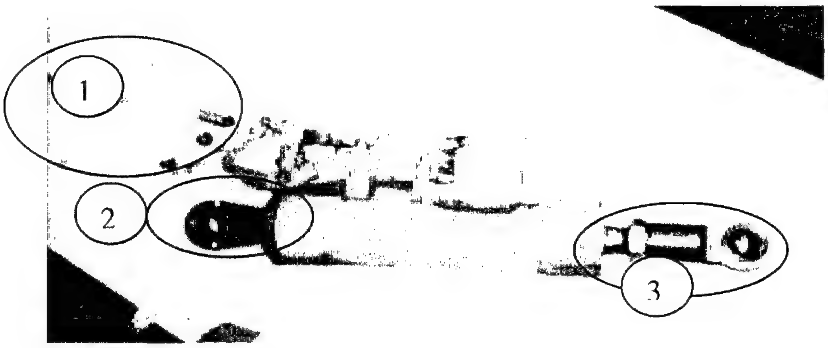


Figure 2. Actuator

The objective of this project was first to investigate and determine the nature of the failure of the hydraulic flaperon actuator. Then, once the nature of the failure was identified, determine alternative materials for the end caps.

Approach:
The nature of the flaperon actuator failures was determined by:

- Generating a solid model for the aluminum flaperon actuator housing and steel plug,
- Creating a finite element mesh for the actuator housing,
- Performing simulations to identify the number of cycles and corresponding loads required to cause this type of failure, and verifying model with subscale laboratory component testing.

Results:
The solid model was generated in Unigraphics by taking dimensions off an actuator sent to NCR[3]. This solid model is shown in Figure 3. After developing the solid model a finite element mesh for the actuator housing and end caps were created (Figure 4).

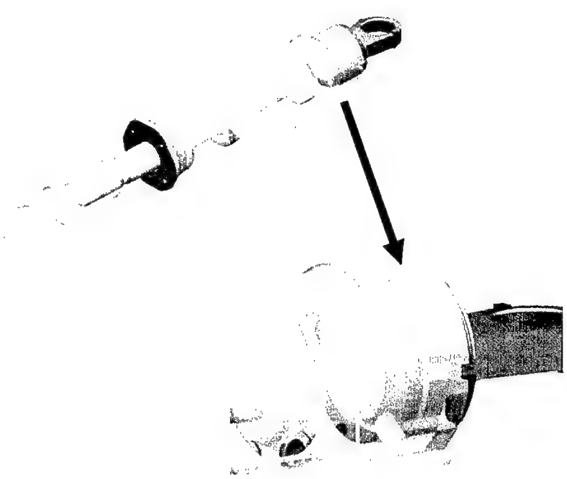


Figure 3. 2D Finite Solid Model of Actuator

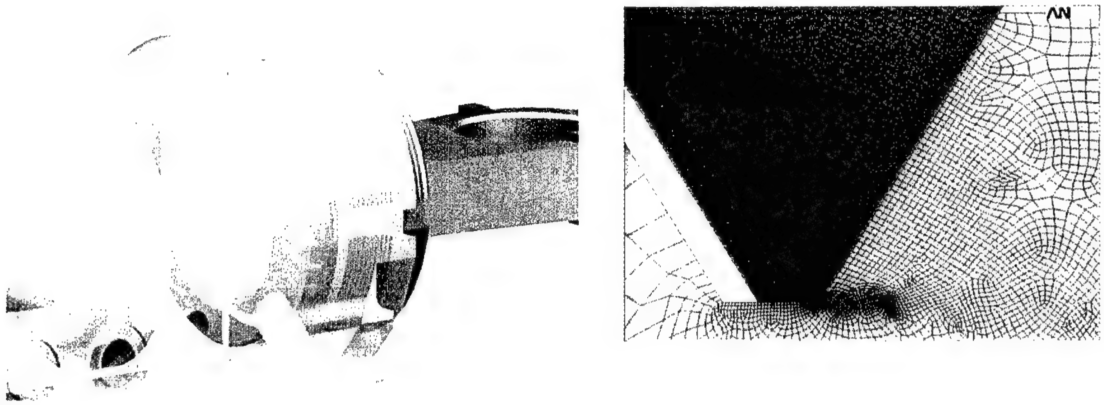


Figure 4. 2D Model of Tread with 0.002" Radius

The results of the Finite Element Analysis showed:

- Severe stresses occur under normal operating conditions at the root of the actuator housing threads.
- Stress results indicate that the yield limit of the material is exceeded under maximum rated operating pressure.

The finite element analysis results were then verified by determining the fatigue characteristics of a simulated actuator threaded connection that replicated the failure mode experienced by fielded units. This was accomplished by developing a subscale hydraulic actuator design and verifying that the stresses were identical to the original design by a 2D finite element analysis. Figure 5 shows the simulated design and actuator testing.

The results of the simulated actuator testing showed:

- The test cylinder exhibited a longer life than Flaperon FEA results — due to better load sharing at threads,
- The asymmetry of design (valve body and ridge) reduces life of part,
- A lower elastic modulus end-cap material improves load sharing at threads for tensile load case and should increase fatigue life, and
- Current test regime is limited by capacity of fatigue tester — Need to develop a new test cylinder design.

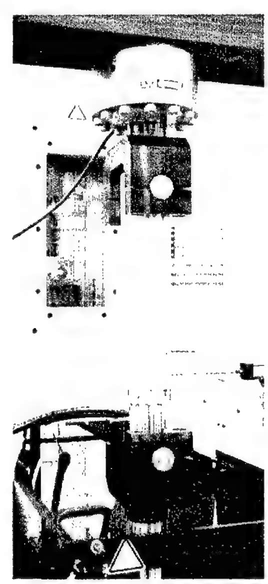


Figure 5. Fatigue Testing of Actuator Threaded Connection

Project: Title: Manufacturing Cost Study EA6B Turtlebacks

Problem:
EA-6B aircraft turtleback assemblies are being refurbished because of corrosion and physical damage. Since the production line for this plane has not run since the early 1990s, replacement parts are no longer available. As a result, there is a shortage of serviceable fuselage assemblies requiring Jacksonville Naval Air Station to spend approximately 200-to-300 man hours or $15,000-to-$18,000 per unit to refurbish fuselage assemblies for EA-6B aircraft.

In addition, many turtlebacks are blown off the aircraft carrier during routine EA-6B maintenance. For this reason, the fleet is looking to fabricate new turtlebacks assemblies. A problem being encountered is that the current turtleback design was produced using metal forming dies that are no longer available. Thus, a new turtleback design needs to be developed.

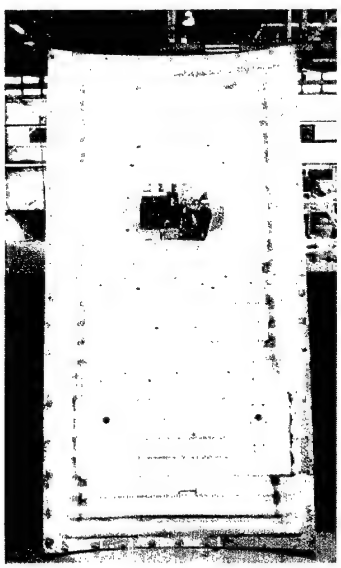


Figure 1. EA-6B Turtleback

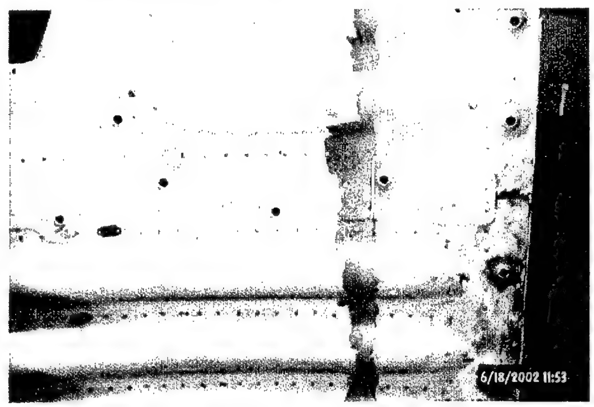


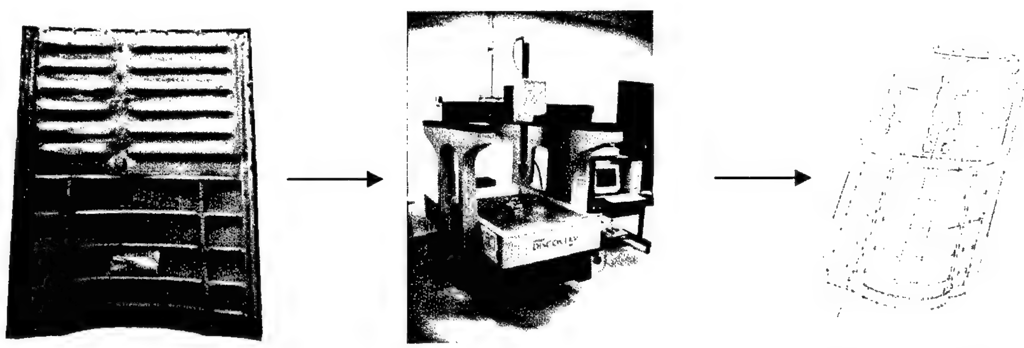
Figure 2. Corrosion Damage on a EA-6B Turtleback

The three assemblies, also referred to as the front, mid and aft turtlebacks, are located on the top of the aircraft between the canopy and tail. The functions of the assemblies are to protect electrical, mechanical, and hydraulic components, while providing easy access for aircraft maintenance. The existing turtleback design consists of an inner aluminum "bubble" layer welded to a smooth aluminum outer skin. The inner "bubble" layer was form using metal working dies that are not currently available. The "bubble" layer provides both strength and rigidity. Although light weight and strong, the closed, sandwiched layer design is susceptible to corrosion, especially around welds.

Approach:
The Systems Modernization and Sustainment Center at the Rochester Institute of Technology has been working with the Jacksonville Naval Air Station on a manufacturing cost study to replace three fuselage assemblies on EA-6B aircrafts with new, more cost effective designs.

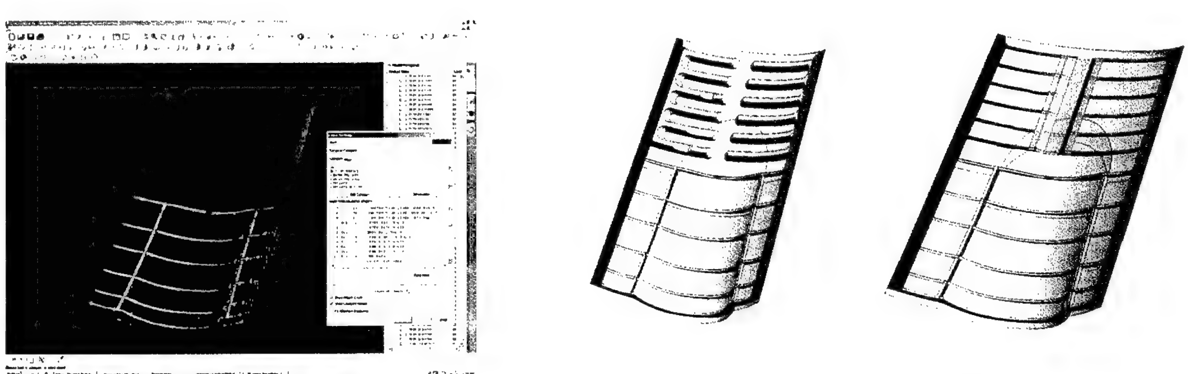
The cost study began by creating a 3D CAD model of one of the three turtleback assemblies. A 3D model allowed for the quick evaluation of alternative design concepts and manufacturability along with the preparation of manufacturing quotes without the need for design drawings. Since the original design drawings were not available for use in creating the 3D model, the model was obtained by reverse engineering an A-6E mid turtleback assembly using a Coordinate Measurement Machine (CMM). The CMM used a contact probe to capture key features of the assembly as points and lines in space. The data was then imported into a CAD system where the points and lines were used to generate a 3D model. From there, alternate designs were created, evaluated for manufacturability, and analyzed to ensure that they were comparable to the original design in strength and stiffness.

Figure 3. Reverse Engineering of Existing A-6E Turtleback



Mid Turtleback　　CMM　　Points and Lines

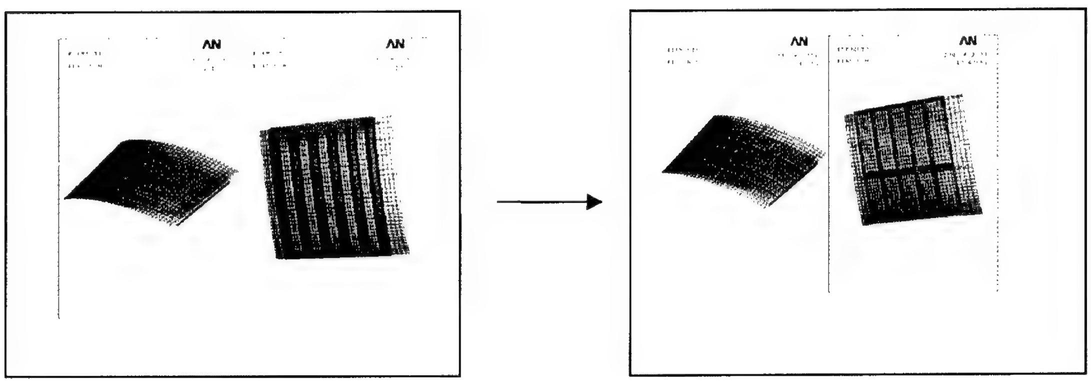
Figure 4. Create 3D Model



Unigraphics CAD System　　Original Design　　New Alternate Design

Results:
Results of the cost study showed that a new alternate design turtleback that replaces the internal "bubble" layer with open rib sections could be manufactured for approximately $6000 per unit based on 30-to-50 units being manufactured This represents a $9000-to-$12000 cost savings per unit over refurbishing existing turtlebacks. In addition, the open rib section design will reduce the likelihood of corrosion damage as compared to the existing design. One time Engineering and Tooling costs associated with this effort was estimated to be $80,000.

Figure 5. Evaluation of Strength and Stiffness of Design

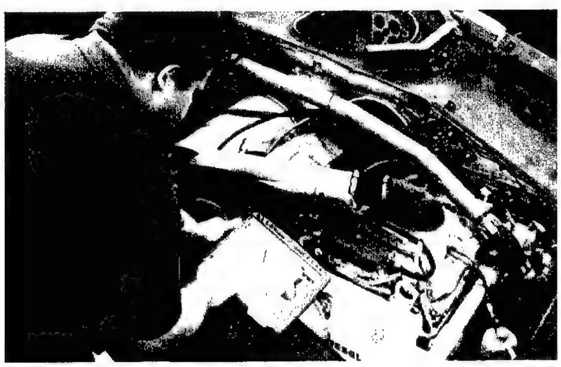


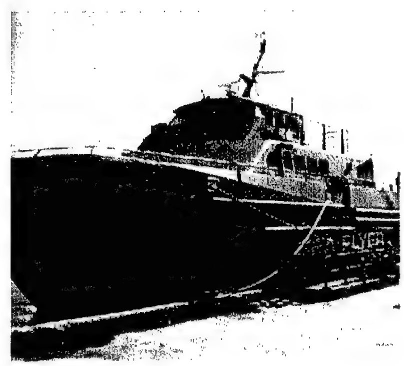
Finite Element Analysis – Original Design

Finite Element Analysis – New Alternate Design

LEEDS™

(Life-cycle Engineering and Economic Decision System)





Program 3: Life-Cycle Engineering & Economic Decision System (LEEDS™)

The Department of Defense faces many challenges in modernizing and maintaining its major systems. Even with the recent budget increases, modernization and procurement budgets are considered far below levels needed for re-equipping the force, and operations and maintenance budgets for upgrade and conversion strain to keep existing systems operating with state-of-the-art capabilities. Additionally, the long cycle times for major acquisition programs are hampering the Department's ability to efficiently and effectively modernize with technically advanced systems.

The Need for Decision Support Tools

Ideally, major existing systems can be enhanced and new systems designed in a way that provides maximum readiness at minimum cost while reducing acquisition cycle times. Processes must exist to aid in the tough trade-off decisions that balance risk, product performance, cost and cycle time considerations. Due to the complexity of the analysis, such processes would greatly benefit from computer assisted decision support tools.

In order to optimize modernization decisions, such processes should be integrated with systems' operations throughout their life cycle. This will not only allow the capture and storage of data critical to the decision process, but will also guide the process to aid in the timing and implementation of remanufacturing/technology insertion cycles in order to minimize life cycle costs.

Life-Cycle Engineering and Economic Decision System (LEEDS™) is both an engineering process and a software tool that is being refined by NCR^3 to address this need. LEEDS™ assists with decisions about the modernization, remanufacture, maintenance and operation of large, complex systems.

LEEDS™ is divided in two major projects, based on where it is implemented within a system life-cycle:

- LEEDS™-R is the application of the process during remanufacturing, at system end-of-service. It encompasses an efficient technical and economic feasibility assessment process. This has been successfully piloted and will provide the foundation for the continued development of the LEEDS™ process and software tool.

- LEEDS™-D refers to the application of the process that commences during system design and continues to end-of-life. It allows global optimization of life-cycle costs through periodic remanufacturing/technology insertion feasibility assessment processes.

LEEDS™-R was originally developed for the Office of Naval Research for use in ship remanufacture and conversion feasibility assessments. In this capacity, the process was designed to evaluate the technical and economic feasibility of system recapitalization. LEEDS™-R was successfully implemented on an inactive SES-200 vessel to determine the feasibility of its use as a main demonstration platform for advanced hull form technology and integrated drive systems. Modernization of the SES-200 was found to be not only technically but also economically sound, generating a savings of $32.6 million per ship. The pilot system developed for ONR has been viewed by Newport News, National Oceanic and Atmospheric Administration (NOAA), Bath Iron Works, Naval Surface Warfare Center (NSWC), Nigel Gee & Associates, Ltd., David Taylor Research Center (DTRC) and Pacific Marine.

LEEDS™-D promotes a holistic approach to optimizing life-cycle system performance through planned modernization and step improvements in technological capabilities. It is designed to improve an owner's decisions relating to life-cycle costs and technology refresh for systems during operating life and at end-of-life. This is accomplished by augmenting the assistance gained by utilizing LEEDS™-R to determine optimal systems remanufacturing options, with the ability to serve as a portal to maintenance manuals, drawings and other references to support system operations, as well as the ability to indicate when proactive measures should occur in order to minimize life-cycle costs and maximize performance.

The evolution of LEEDS™ focuses on improving an owner/operator's decisions relating to equipment life-cycle costs throughout system operating life, not only at end-of-life. This will be achieved by positioning LEEDS™-D to serve as an efficient method for the identification, collection and storage of pertinent system specifications from initial design and build activities. These specifications, in addition to the wealth of condition, performance and cost data that accumulates during systems' life-cycles, will be warehoused in a centralized repository and will allow LEEDS™-D to serve as an on-board maintenance support tool as well as a high-level performance monitor of key systems. This will enable users to assemble and manage enormous quantities of design, cost, condition, and performance data. Performance and cost alternatives will be identified and updated easily by enabling users to frequently revisit maintenance, modernization, remanufacturing, operating costs and other variables throughout the life of a system.

By providing the ability to compare competing options, the Department of Defense can make life-cycle decisions to meet the goals of lower operating costs, higher reliability and enhanced performance. With LEEDS™, the Department of Defense can easily review and analyze maintenance, modernization and remanufacturing decisions.

The LEEDS roadmap illustrated in Figure 1 describes the development of the technologies embedded within the LEEDS application. This same chart incorporates the specific projects that help to demonstrate the growing capabilities. The technology cycle for the LEEDS process was based in the fact that much of the information that was

helpful in remanufacturing a military platform was available in many disjointed data streams. The LEEDS technology roadmap intended to combine this data and make it available for quick referencing inside one large structured database that was relationally related to the functional hierarchy of the weapon system. The usefulness of the relational database drove the next technology effort of LEEDS by making the database portable in a web based format for access by remote users. The web portal format would allow multiple program teams to call on the same data for reference, data storage and retrieval and report development. As the functionality of the database grew with additional users, a more forward looking growth approach for data warehousing was envisioned which drove the technology shift away from the MS Access database and into a SQL database environment.

The SQL database affords greater security elements as well as the means to assign a date stamp to items being entered into or deleted from the data architecture. Further, the technology roadmap introduced the features for LEEDS that allowed synchronization between the primary database and disconnected databases. The means of continuous data link could not be counted on so the LEEDS development enabled two separated databases to be synchronized when a data pipe line was available. The natural growth of the LEEDS system would be the implementation of an automated condition monitoring package. The prognostic packages under development in the Asset Health Management program, would reduce the time consuming data collection needed when conducting condition assessments of pieces of equipment. Future development of LEEDS will integrate decision support tools that support the maintenance task to improve trouble shooting efficiencies.

The primary projects that were conducted under the LEEDS program include:

- Life-Cycle Management & Software Development — Sponsor / ONR
- Sea Flyer Overhaul Support — Sponsor / ONR
- LEEDS – Light Armored Vehicle & HMMWV Fleet Functionality Sponsor / ONR
- LEEDS – Design Capture implementation on the Kilo Moana — Sponsor / ONR – Lockheed Martin
- LEEDS – Monitoring Implementation on the HDV-100 — Sponsor / ONR – Navatek

LEEDS
Technology Development Roadmap

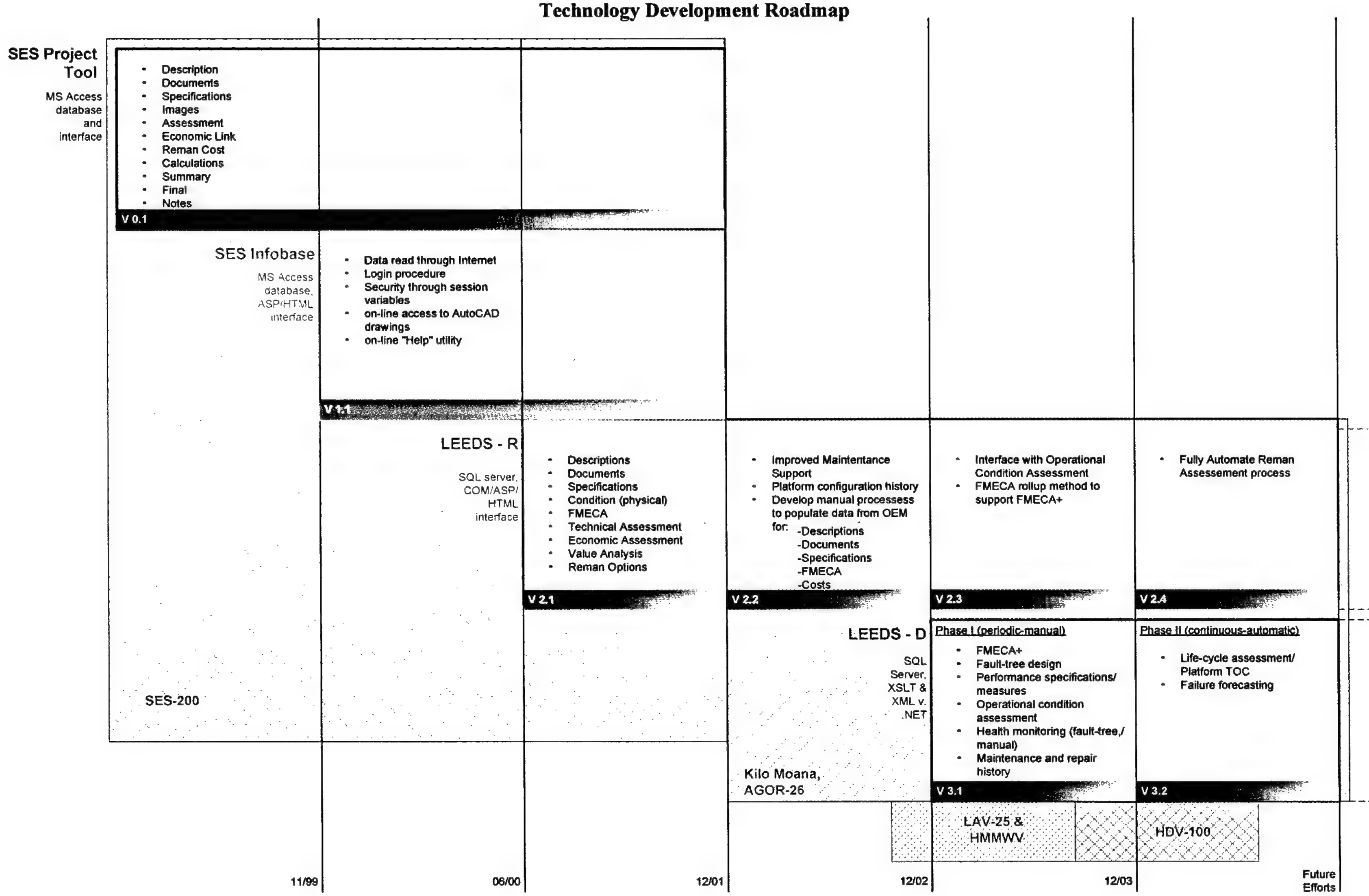


Figure 1

Life-Cycle Engineering & Economic Decision Systems

PROJECTS

Project Title: LEEDS Life-Cycle Management & Software Development

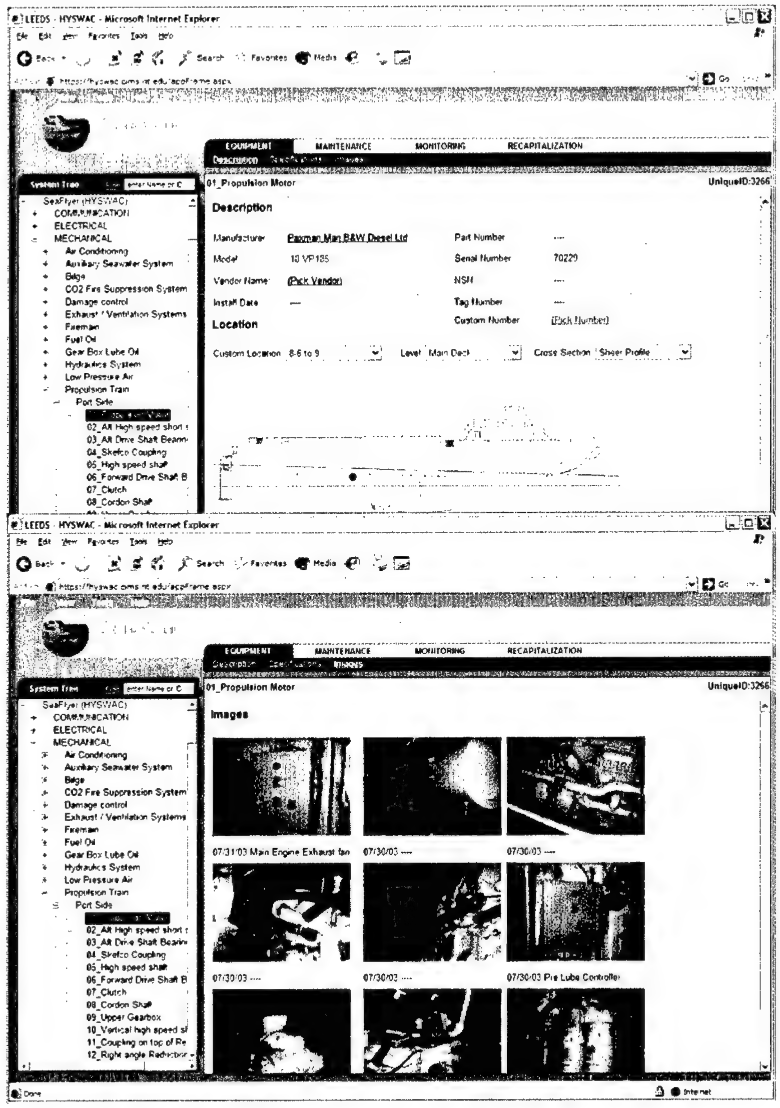
Problem:
Time consuming approaches have been attempted in the Department of Defense to ascertain the cost associated with upgrading weapon platforms. The cost drivers inevitable drove the final decision sometime to the detriment of better engineered solutions. The Office of Naval Research was in need of a decision support tool that provided a well defined process to make clear decision on the upgrades of aircraft, ships and ground platforms, utilizing both a balance approach of engineering and financial inputs.

Approach:
Life-Cycle Engineering & Economic Decision Systems (LEEDS) is a process and a collection of tools to manage life-cycle decisions for complex systems. It is a method to modernize existing systems and design future products, increasing readiness and performance and reducing ownership costs. The database decision support system implements a long-term system management approach. It can be easily updated to frequently revisit maintenance, modernization, remanufacturing and operating costs to optimize returns on investments.

The LEEDS process was modeled after engineering analysis used in the SES-200 Remanufacturing and Conversion Feasibility Study. The first-generation database was developed concurrently with the aforementioned project as a data store and analysis tool. Developed in MS Access, the underlying database engine was designed for use within a small work group and was limited in scalability and robustness. A second-generation database was then constructed to enable access to the same underlying data store as the previous generation via the Internet. This was accomplished using Microsoft s active server pages environment, and allowed only read access to ship information. Additional work was conducted to enable username / password protection, to allow on-line access to files, and to improve the application s usability. A third generation evolution of the software was started to allow read/write access to data over the web. Our current generation of software has all of these features plus additional strengths in usability, data security and access control. It is built upon industrial grade server products, using the latest version of Microsoft s server systems, Windows Server, Internet Information Server, and SQL Server 2000. This design allows for an extensible scaleable system, which will meet the data storage needs of LEEDS for a number of years to come.

Our current system has two significant features, the first is a data change history, as users make updates to data a copy of edited data is stored in a change history table. Giving visibility to the changes as a function of time and allow auditing of users changes. A future extension of this feature is to roll back the whole system to a point in time. The

second new feature is the ability to control user s access to items in the system hierarchy. In prior versions there was uniform access rights to data, now we can create groups that have very granular access rights and then assign people to these groups.



A third major are of improvement was the handling of large document sets. Several of our LEEDS instances have a number of very extensive manuals some already converted into PDFs. We needed to work out the methodology of splitting the PDFs into segments that would be of acceptable size for use over the internet and then provide the links so that when an item is selected in the tree, say an alternator, that the hyperlink to the manual opens the correct document and more importantly jumps to the alternator section for viewing.

Results:

Efforts have led to the formalization of an engineering process to evaluate the feasibility of remanufacturing at product end-of-life. This process is embodied in the LEEDS software application. This application provides:

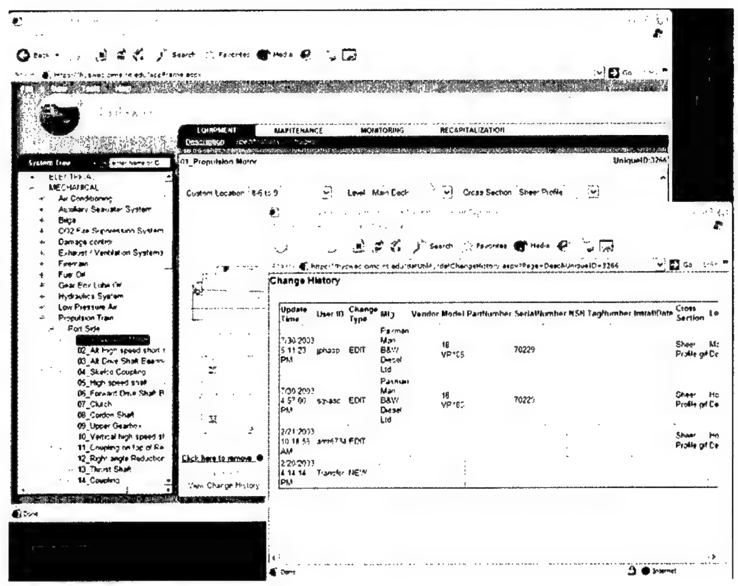
- One convenient location to store ship information
- Automation of analysis tools and economic archiving
- On-line viewing of CAD files, manuals and maintenance procedure videos
- Password-protected access to web site, user group specific hierarchy access and editing rights
- On-line help utility

Improvements to the database are expected to continue into the next funding year. Anticipated upgrades are to include additional maintenance support, such as case based reasoning for problem resolution. Another area is developing the infrastructure to tie LEEDS into our AHM architectures.

Project Title: LEEDS – Sea Flyer (HYSWAC-SES200) Overhaul Support

Problem:

When a system goes through a remanufacturing/overhaul process, significant changes can be made to the ship structure and the systems within. Our early version of LEEDS contained a snapshot of the system, with no visibility of when the last update occurred. If an update occurred to a component the new data overwrote the original entry. Extending beyond the software tool is the issue of how to maintain a dataset as a system goes through an extended remanufacturing/overhaul process, balancing data entry tasks of keeping a moving target up to date with manpower resources/data availability while not entering in modifications that will have changed before the system is re-launched.



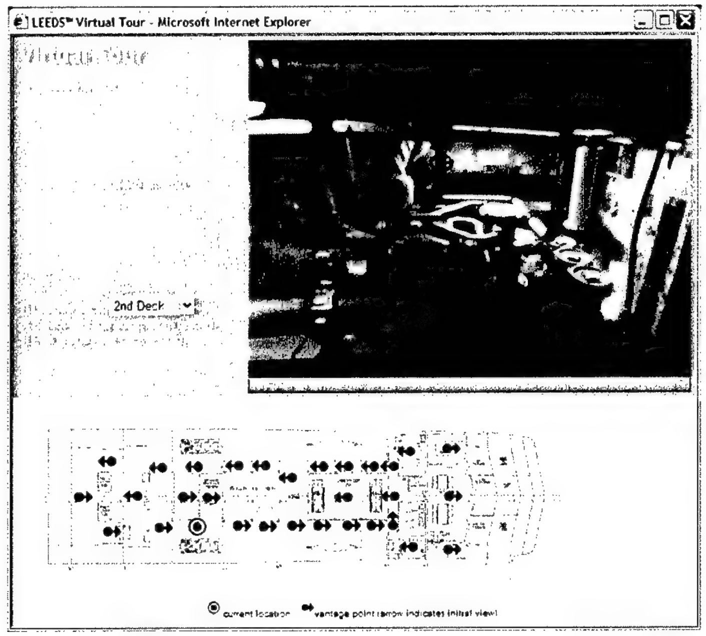
Another area that was brought to light during the Sea Flyer overhaul was the requirement of the specifier to be able to virtually tour the ship from a remote location. In this case the specifier in Washington DC had concerns for crew safety if a fire broke out in the engineers space. The CO^2 system would pressurize the space; potentially forcing the doors shut depending which direction they closed, and catastrophically keeping the crew in. Drawing of the engineering space did not indicate door swing directions.

Approach:

For the issue of tracking changes to the system with time we added a change history link to each data view, bringing up a corresponding change history. When the user clicks on the change history link on each page, a subsequent page brings up a report showing who made the change, when and what type of change — new, editing or deletion of record. As seen below the change history can also be used to trace user edits for auditing purposes.

Besides tracking the changes of individual records, in the case of electronic documents that were uploaded into the LEEDS, the LEEDS system keeps historical versions of documents and images uploaded to the system. Allowing users to view the change history for an item and for example see the image history associated with the item.

For the issue of virtually touring the ship, SMS researched a tool set that would allow us to capture images off a special parabolic lens, and then using a post processing software tool, generate near spherical images that users can navigate using an Apple QuickTime plug in. The plug in allows movement left/right and up/down plus zoom.



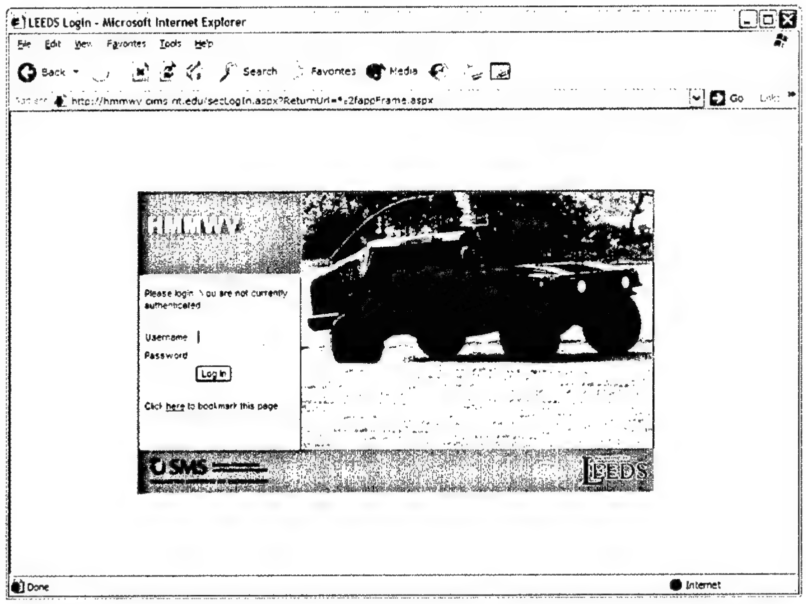
Access to virtual tour was through a set of pages that used icons overlaid onto ship diagram and indicating the initial viewpoint. A set of controls on the page allow selecting different levels of the ship.

Results:

Using the Sea Flyer as demonstration of the LEEDS technology has been very informative for the development team. Direct customer input has driven several new areas of development, such as the change history and virtual tour both of which have been very well received. The LEEDS group has successful deployed a system on board ship the Sea Flyer for demonstration purposes. The system includes a kiosk with a server running the latest Windows operating system, 18 LCD display, a portable disk for data backup and an uninterruptible power supply. As part of the installation we placed 3 wireless access points, one on the kiosk, a second near the generators, and the third in the engineering controls space. These access points allow users with wireless laptops and tablet PCs to view and modify the LEEDS data from nearly anywhere on the ship.

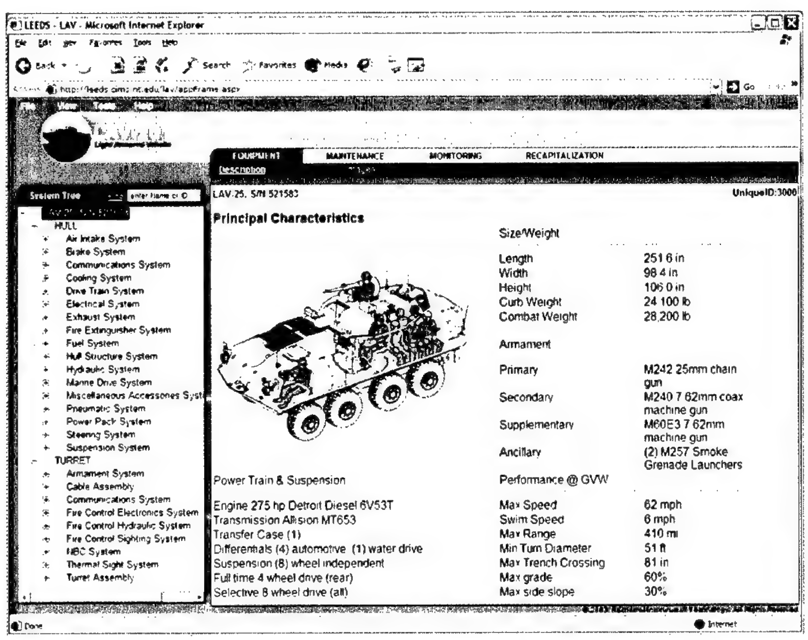
The virtual tour capability was also very well received, besides helping with the fire door issue, it has allowed disparate parties to view and discuss issues while viewing the same item over the internet. The tool also has great use for providing briefing and orientations without the expense of visiting the vessel.

Project Title: LEEDS – LAV & HMMWV Fleet-base Functionality



Problem:
As part of the Asset Health Management program, NCR[3] acquired several military vehicles, 2 different HMMWV s and 3 different Light Armored Vehicles (LAV s). Custody and periodic maintenance were the responsibility of NCR[3]. The current configuration of the LEEDS software had not been tested on a fleet base project. The software would need to be modified to handle the repeatability of data and the issue associated with tracking maintenance on fleet equipment. NCR[3] was tasked to apply the LEEDS tool as an in-house repository for the maintenance related events and as a repository of all data for both vehicle designs.

Approach:
This project provided an excellent opportunity to monitor the users of the LEEDS system real time. Software designer were able to closely monitor the workflow of the data entry personnel and the vehicle maintenance personnel. This close visibility enabled rapid modification to the software code contributing to improved database performance.

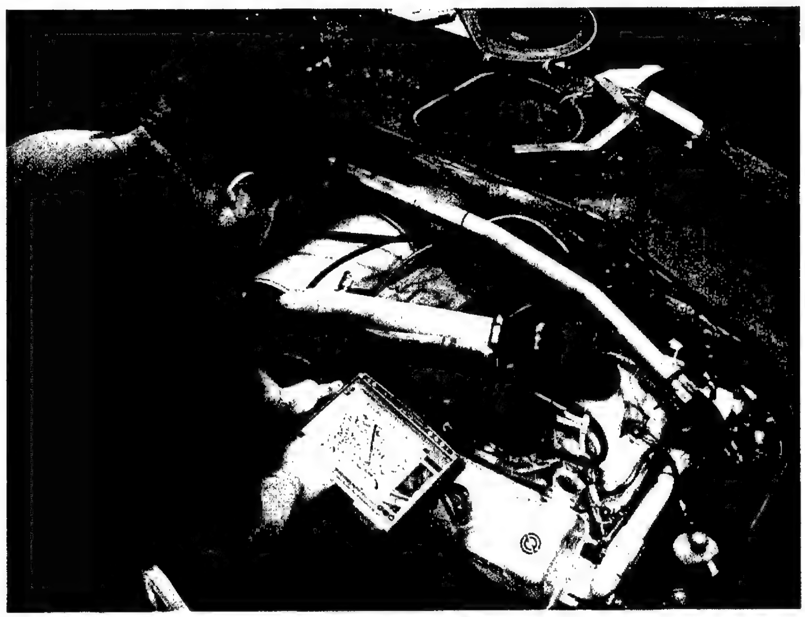


An issue these observations yielded was how to manipulate the large PDF manuals. Development time was spent on how to split up PDFs, and provide a user interface for uploading the manual and entering in link information. Manuals that are scans of the original document were run through an optical character recognition program to make them searchable.

Results:
Currently there are 858 items listed in the database for the two vehicle types. For the LAV there are 342 manual sections totaling 445MBs of PDF available online. Along with over 1100 photos and 468 exploded view drawings.

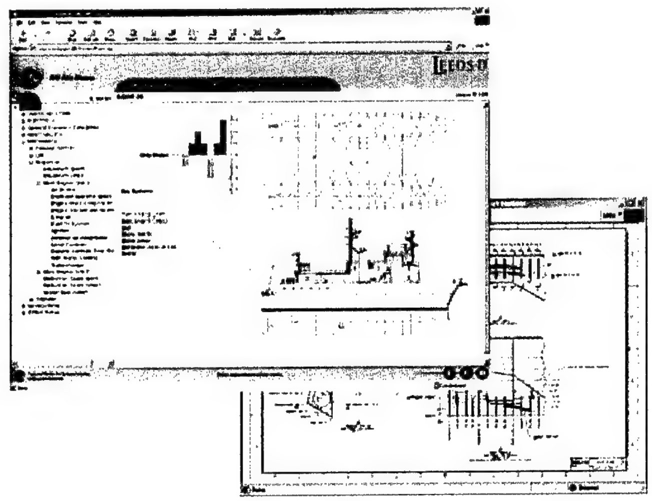
The LEEDS LAV site was used many times as part of our AHM demonstrations, allowed visitors to see our vision for AHM, from getting detailed prognostic data remotely from the vehicles to a maintainer being able to walk up to a vehicle and view the pertinent manuals to correct the components fault.

LEEDS proved an invaluable tool for doing research on the vehicles and there sub systems. Allowing engineers to sit at there desks and research a system while just using there browser. Many of the PDFs are searchable, allowing quick access to pertinent sections.



Project Title: LEEDS – Design Capture Implementation on the Kilo Moana

Problem:
Although remanufacturing offers a cost-effective means to recapitalization of large platforms, it requires a significant amount of effort to collect and analyze the data necessary for engineering activities. Often, reverse engineering must be employed to recreate systems' data due to often neglected or lost information sets. However, making end-of-life decisions can be simplified if preemptive measures have already been in-place to archive crucial data.



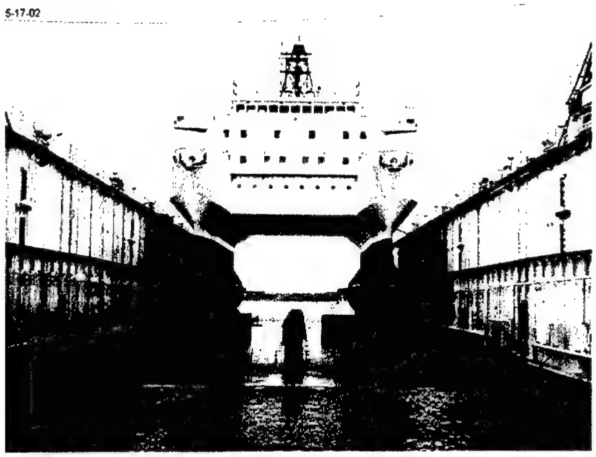
Recognizing the life-cycle benefits to establishing a well-maintained archive, the R/V Kilo Moana (AGOR-26) was chosen as the initial pilot of the LEEDS™-D process. One of the main tenets of this process – design capture – plans for the deliberate identification, collection and storage of pertinent system specifications attained directly from initial design and construction activities, thereby averting the need for future reverse engineering. The R/V Kilo Moana, operated under the auspices of the University – National Oceanographic Laboratory System (UNOLS), was identified as an ideal candidate for this pilot due to its recent construction for the Office of Naval Research.

The pilot will ultimately prove the usefulness of implementing the LEEDS™ process at the conclusion of platform design, in order to support remanufacturing and life-cycle decisions throughout operational life, in addition to those at end-of-life.

Approach:
Design capture of ship systems was achieved by collaboration with Lockheed Martin Corporation. Through working with those responsible for the ship conceptual design and overall construction, data collection efforts focused on cataloging detailed design information such as equipment serial numbers, locations aboard ship, digital images, vendor contacts, and system functions.

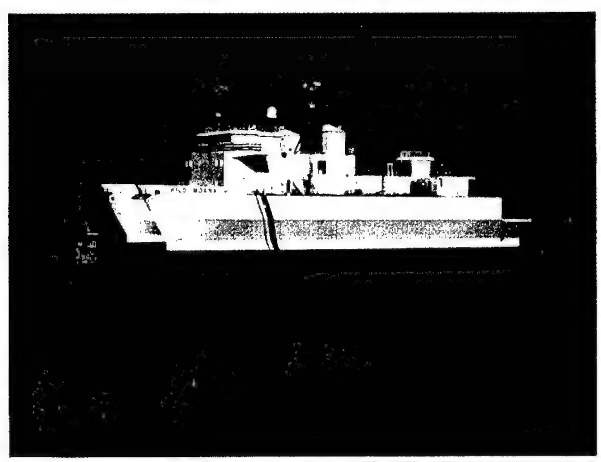
LEEDS™ document management practices were employed to accommodate the volumes of engineering documents obtained from Lockheed Martin including multi-sheet drawing sets and equipment manuals. Drawings, which ranged from machinery arrangements to electrical on-line schematics, were mostly received in a digital format. However, supplementary meta data was

added in order to facilitate navigation between the drawings and LEEDS" database. The drawings were then exported in a format optimized for on-line review and then uploaded to the database archive. Equipment operations and maintenance manuals were also digitized, and processed with character recognition software to enable full-text searching directly from LEEDS".



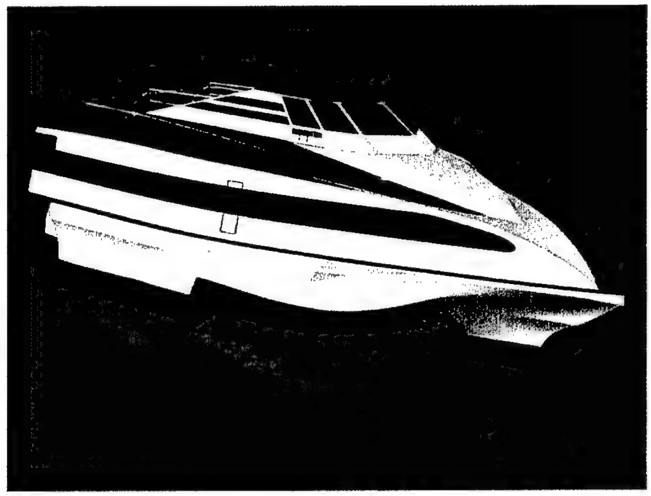
Advanced engineering analysis began, with the participation from Lockheed Martin, on ship systems in order to assist future recapitalization efforts. Failure modes effects and criticality analysis (FMECA) was conducted on a mechanical system in order to supplement readily available information. In the future, the results from such analysis will also help support equipment failure troubleshooting and case base reasoning features.

Results:
At the time of this writing this project is still in progress, with final data collection of ship systems currently underway. The progress of data collection activities is dependent on ongoing dialogue between NCR3 and the School of Ocean & Earth Science & Technology (SOEST) at University of Hawaii, who is charged with operation of the R/V Kilo Moana. Collaboration with SOEST is required since the ship is presently in service and is constantly rotating between research tours. It may be necessary for the ship s crew to assist with the final collection of as-built equipment specifications, especially since several systems have been modified significantly since the ship entered service.



In addition to finalizing data collection, efforts are currently underway to install the LEEDS" system on-board the R/V Kilo Moana. This will entail installation of a server and integration with the ship local area network. Data synchronization functions have already been developed in order to allow synchronization sbetween the ship database, and a replicated database located on-shore in order to manage remote support of equipment. Locating LEEDS" on-board the ship will permit validation of the operational value of archived equipment information to maintainers through regular use of LEEDS".

Project Title: LEEDS – Monitoring Implementation on the HDV-100



Problem:
It has been proven that remanufacturing offers significant benefits to equipment recapitalization at end-of-life. LEEDS“-R embodies the tools that guide this decision process. However, additional benefits may be gained by implementing incremental modernization cycles throughout a platform s life-cycle. LEEDS“-D is designed to meet this challenge by improving an owner s/operator s remanufacturing decisions through monitoring systems during operating life, not only at end-of-life. Such a process would aid in the timing and implementation of remanufacturing and technology insertion cycles in order to minimize life cycle costs.

Although monitoring may be achieved though a component-level condition-based approach, it would require considerable infrastructure and customized engineering to make it work properly. It is the hope that LEEDS“-D will be able to circumvent this difficulty by approaching monitoring from an opposite direction, which trends platform-level inputs/outputs that may be used to gauge overall system performance. From this high-level approach to platform monitoring, LEEDS“-D would give visibility to a platform owner/operator as to when to invoke the remanufacturing process.

The HDV-100 vessel was chosen to pilot the LEEDS“-D monitoring initiative. At the time of project initiation, the approximately 98 L.T. displacement ship was under construction by Navatek LTD. The HDV-100 was an excellent candidate since design data could easily be recorded by the LEEDS“ process and the complexity of the ship was considered to be ideal for the intended scope of the monitoring system.

Approach:
Initial work focused on the population of a LEEDS“ database including systems specifications and documentation. Although the ultimate goal of the database is to reflect the as-built configuration of the ship, this activity was commenced during ship construction. Creation of the database will allow the project team to familiarize themselves with ship systems and aid in the development of a monitoring plan.

Systems critical to ship operation or pose high risk of failure will be identified. Analysis of signals already available from such systems will be conducted in order to identify the subset of

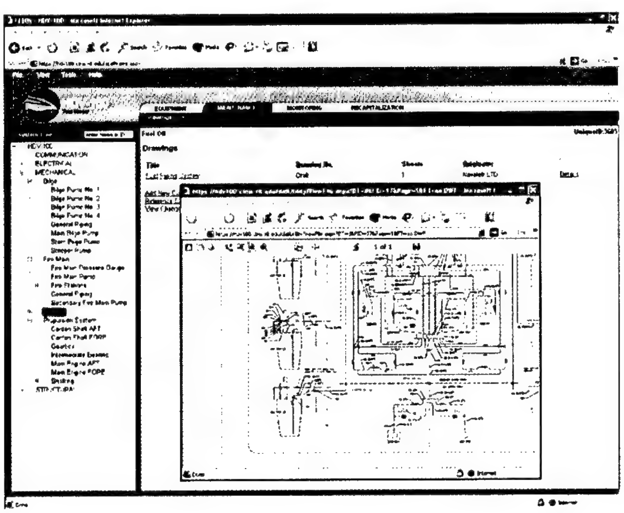
information most critical to a ship operator. No additional sensors will be installed on the ship. Decision models will be constructed to trend and interpret the acquired data. A graphical user interface within the LEEDS“ software will be developed to represent the key systems performance monitor.

Installation of the LEEDS“ software/hardware aboard ship will require integration with onboard signals and computer networks. A separate LEEDS“ server and monitor will be installed, along with a supplementary local area network if the existing network is deemed insufficient, to allow remote access from ship spaces. Mechanisms for remote access to on-board server while ship is in-dock will also be investigated. Final testing of the data acquisition system and LEEDS“ will be conducted to corroborate the accuracy of the monitoring system.

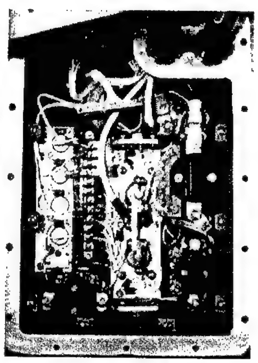
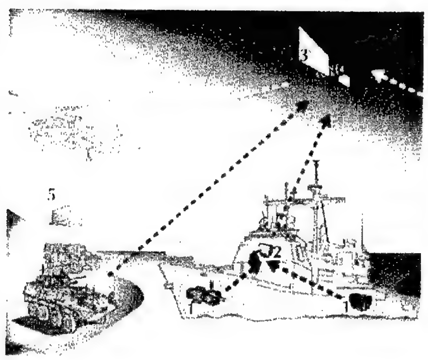
Results:

At the time of this writing this project is still in progress, with initial data collection of ship systems currently underway. The progress of data collection activities is directly dependent on the ongoing detail design of ship systems. The final collection of as-built specifications will coincide with the end of ship construction activities, expected to conclude in April 2004.

Once the majority of ship systems have been documented, it will be possible to identify candidate systems for monitoring. Based upon the systems selected, decision models will be developed and integrated into LEEDS“. It is planned that the completed system will be ready to install aboard ship in May/June of 2004, to evaluate and validate platform monitoring functions.



Asset Health Management

Program 4: Asset Health Management

Improved readiness of new and existing weapons platforms and improved battlefield information access are necessary to meet the military needs of the early twenty-first century. These challenges must be met without increasing operations and support costs or manning.

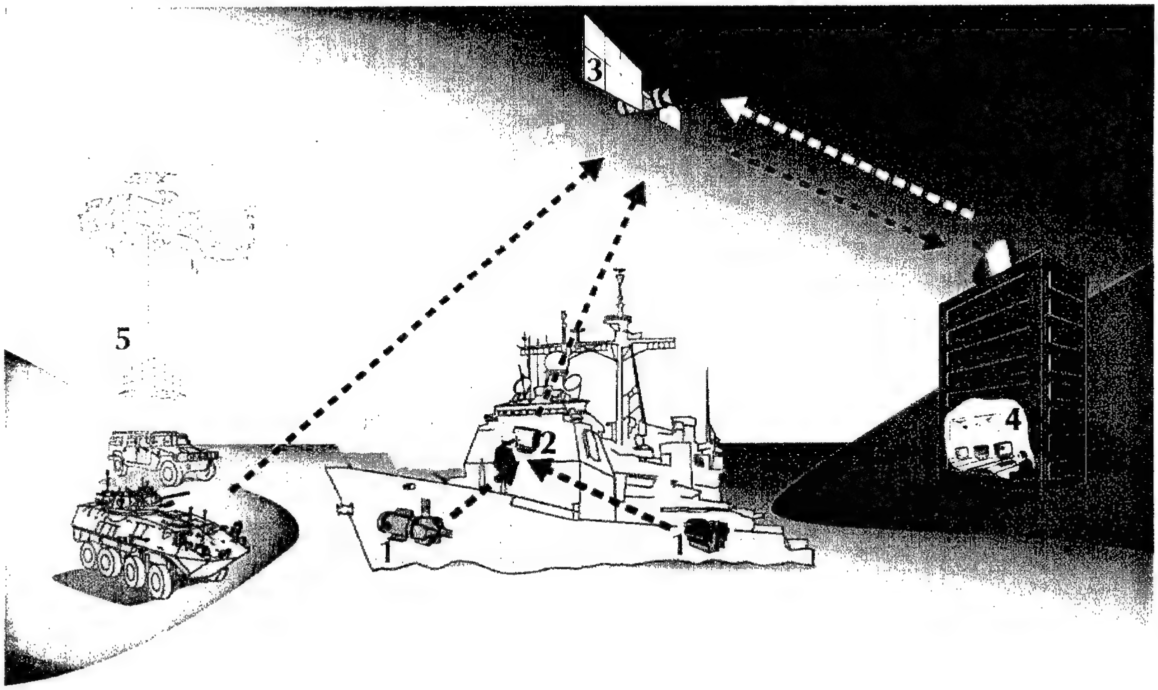
Asset Health Management represents a set of technologies that can make a strong contribution to addressing these challenges. RIT has developed a set of core capabilities in Asset Health Management under this grant. Our work to date has focused on resolving issues that affect the technical and economic feasibility of asset health management deployment for Marine Corps ground vehicles. Several system architecture iterations have been completed, and a broad range of functional capability developed. Recent efforts have focused on the development of a fieldable system design for the Marine Corps' Light Armored Vehicle (LAV). The work supported by this grant has demonstrated the improvements in operational effectiveness and reduction of maintenance effort that can be achieved through the application of asset health management technologies.

Asset Health Management is a holistic approach to managing the operation and maintenance of complex equipment. Equipment readiness is maximized while controlling operations and support costs. An effective asset health management system integrates the weapon platform into its support systems: maintenance, logistics and supply, and engineering. This requires mechanisms for consolidating and communicating platform operational data to those support systems, and feedback mechanisms for making changes to operations and support procedures, or the weapon platform itself. At its core, an asset health management system requires an ability to monitor the condition, degradation, and health of the equipment. In its most effective state, an asset health management system enables proactive response to operational problems.

The illustration on the next page (Figure 1) shows a vision for asset health management. Monitoring systems on-board the platform track operational data, diagnose the root cause of failures, and predict failures before they occur. Crew members are notified of potential equipment problems and can adjust the operation of critical systems in order to prevent mission failures. Tactical communications networks provide remote access to on-vehicle data giving Command and Control visibility into equipment health and supply levels (particularly fuel and ammunition). Mission plans can be updated to react to equipment failures, or maintenance teams (or spare parts) and supplies can be rapidly deployed to exactly where they are needed improving operational effectiveness. Unit maintenance efficiency is optimized by eliminating unnecessary or incorrect maintenance actions. Platform data is captured and trended across the entire fleet providing program managers the information that they need to manage fleet engineering upgrades. This also provides advanced warning of failure trends that enable anticipatory logistics. The ability of the logistics system to anticipate failure trends and have repair parts available, and the ability of maintainers to predict failures of particular platforms results in huge improvements in operational asset readiness.

Figure 1

Asset Health Monitoring and Logistics Support Model



1 System Health Monitoring

Sensors are placed on all key systems. Smart systems report their health based on sensor data. Considered data may include temperature, vibration, noise, contaminants in oil and other performance criteria.

2 Platform Asset Management

System health information is used to support decisions with respect to platform and equipment operation, maintenance, and life-cycle management.

3 Platform Status Reporting

Data transmitted from each platform includes only that information necessary for fleet monitoring, support and supply.

4 Remote Support and Monitoring

Fleet Health and Operations Monitoring — the ability to maintain extensive historical databases across the fleet enables knowledgeable personnel to make platform and fleet life-cycle decisions.

Technical/Logistical Support — on-platform personnel have access to remote government and contractor engineers for problem resolution. Actual or forecasted failures would trigger supply systems.

5 Resupply

Resources such as fuel, ammunition and in-field maintenance material are then transported to those platforms requiring support.

The vision above discusses a number of asset health management system capabilities which can be implemented together or separately. The chart below summarizes some of the enabling technologies for each of these asset health management system capabilities.

System Capability	Enabling Technology
On-board diagnostics and prognostics	- On-board databus network and diagnostic computer - COTS (commercial off the shelf) sensors and components - Knowledge and model based systems for diagnostics - "Physics of failure," trend, and model based prognostics
Maintenance Aiding	- On-board diagnostics and prognostics - Knowledge based maintenance aiding system - Electronic portable (point-of-maintenance) aids
Remote monitoring (telematics)	- Data transmission and security mechanisms - Data analysis and visualization tools - Vehicle information interface description (for data transport)
Fleet trending and anticipatory logistics	- Data collection mechanism (e.g. web-portal) - Data analysis tools (data mining, trending and prediction, etc...)

The full benefits of an Asset Health Management system are realized when all of the system capabilities above are implemented in a seamless system-of-systems approach. However, there are still technology gaps in a number of areas that must be closed in order to achieve the full functionality. The research goals of the Asset Health Management program are closely aligned with the Materials Aging and LEEDS (Life-cycle Engineering and Economic Decision System) programs at the RIT Systems Modernization and Sustainment Program to fill these technology gaps while producing useful applied solutions for a variety of DoD programs.

Figure 2 illustrates how the technology being developed by the Asset Health Management program is filling the technology gaps while producing useful applied solutions for a variety of DoD programs. A driving principle behind our research program is to field validate our technology and work with our DoD partners towards successful transition.

In the research supported by this grant, the Asset Health Management program has focused on developing and demonstrating technology for on-board diagnostics and prognostics for legacy military ground vehicles. Demonstration systems were developed for the USMC (United States Marine Corps) HMMWV (High Mobility Multi-Wheeled Vehicle) and LAV (Light Armored Vehicle). The LAV program has subsequently grown into an Advanced Technology Demonstration (ATD) program for the LAV Program Manager's office. Initial technology concepts are currently being transformed into military spec systems for the LAV, and the NCR3 on-board diagnostic system is an integral part of the Integrated Data Environment (IDE) being developed by PM-LAV. NCR^3's on-board system will interface with a hand-held point-of-maintenance computer for maintainers, and also the PM-LAV Integrated Data Environment. An additional LAV program initiated during this research grant and carrying forward into a subsequent grant with ONR is integrating commercial off-the-shelf automotive sensor technology into the NCR^3 monitoring architecture for the LAV.

Asset Health Management
Technology Development Summary

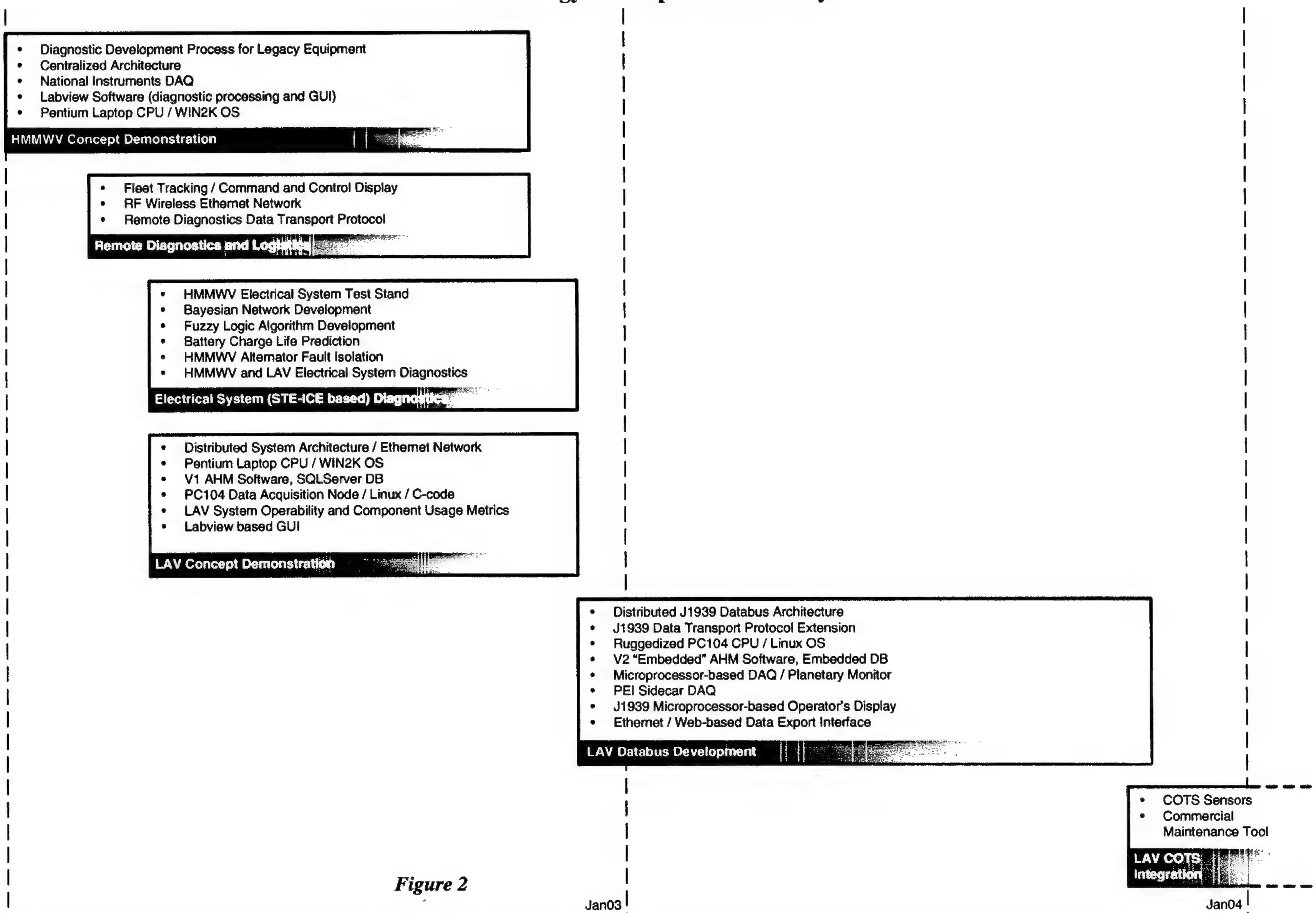


Figure 2

As shown in figure 2, the primary projects that were conducted under the Asset health Management program include:

- Asset health management Concept & Development
    - HMMWV On-board Diagnostic System — Sponsor / USMC MATCOM
    - Light Armored Vehicle — Sponsor / PM-LAV Office
    - Remote Diagnostic and Logistics — Sponsor / ONR
- STE –ICE Based Electrical System Diagnostics — Sponsor / ONR, USMC 8th Tank Batt.
- Light Armored Vehicle Databus Development — Sponsor / PM-LAV Office
- Light Armored Vehicle COTS Technology Integration — Sponsor / PM-LAV Office

These programs will be described in detail in the following pages.

Asset Health Management

PROJECTS

Project Title: Asset Health Management Concept Development

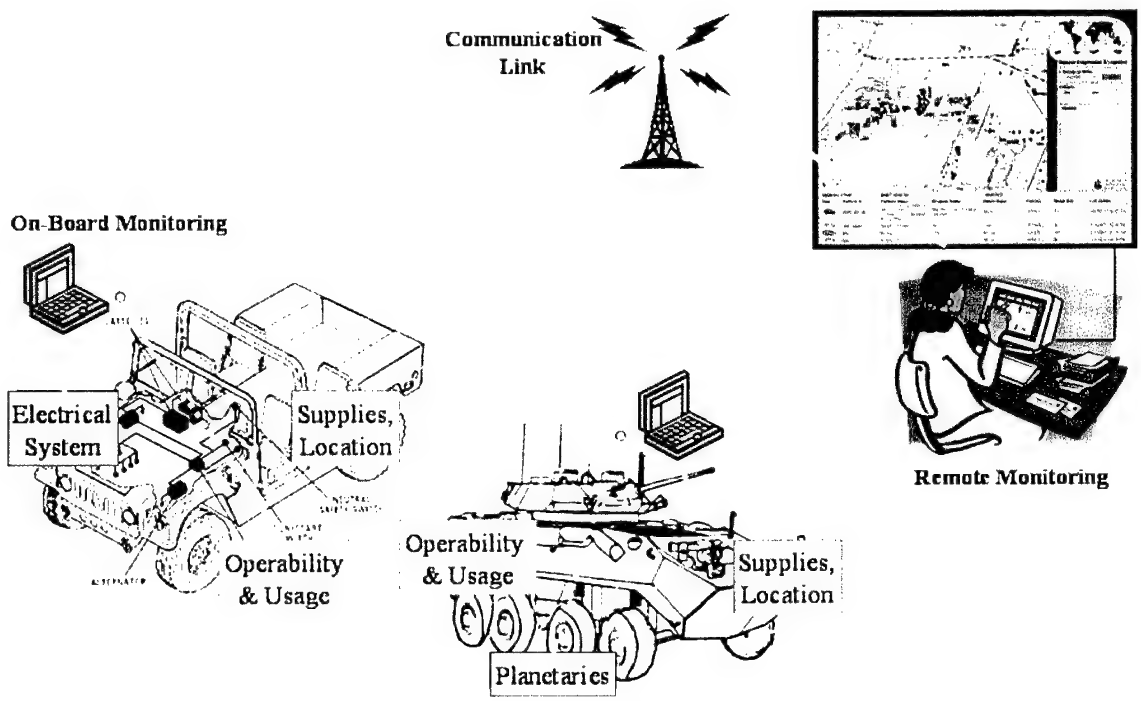
- **HMMWV On-board Diagnostic System**
- **Light Armored Vehicle On-board Diagnostic System**
- **Remote Diagnostics and Logistics**

Problem:
Many legacy military vehicle platforms have high operating and support costs and are difficult to maintain at required readiness levels. In addition, advances in information technology are driving new concepts in military command and control, as well as new logistics and support concepts that will require military platforms to be able to automatically report their operational status. On-board health monitoring and diagnostic systems are being designed into new platforms due to these issues. However, a cost effective means of upgrading legacy platforms with this new capability is required.

Approach:
The technology focus for this concept development program was on-board diagnostics and monitoring technology for ground vehicles. However, we also wanted to be able to assess the requirements for telematics solutions for military ground vehicles and included remote monitoring in the requirements for our concept demonstration. Our technology development target for this effort was legacy platforms and we identified two program managers of Marine Corps ground vehicles (HMMWV-Highly Mobile Multi-Wheeled Vehicle and LAV-Light Armored Vehicle) that had an interest in developing diagnostic technology for their legacy platforms. Both of these programs loaned us vehicles for our concept development purposes.

Monitoring system requirements were developed with input from these program managers, and also from advanced logistics concepts being developed by the USMC and ONR. The autonomic logistics concept being developed by ONR and the USMC requires that fielded equipment report its operational status on a regular basis: GPS location coordinates, fuel level, ammunition level, and overall health status. Our development concept is shown in the figure below. Our goal was to implement an on-board monitoring system on a single HMMWV and LAV, and have both vehicles report their operational status over an RF wireless link. The figure identifies the types of information to be monitored on-board the vehicle. The green boxes represent location, ammunition level, fuel level, and could include other critical supplies (e.g. water, medical supplies, etc.). The orange boxes represent high-level information about the state of major vehicle systems. This includes an overall assessment of whether the systems are fully operable, degraded, or down. In addition, usage metrics can be captured and recorded during the vehicle operation (engine hours, RPM excursions, etc.). Both of these types of assessments can be made with limited sensor sets and without extensive algorithm development. The blue boxes represent more thorough analyses of the health of targeted systems. This may include diagnostic assessments (what is broken) or prognostic

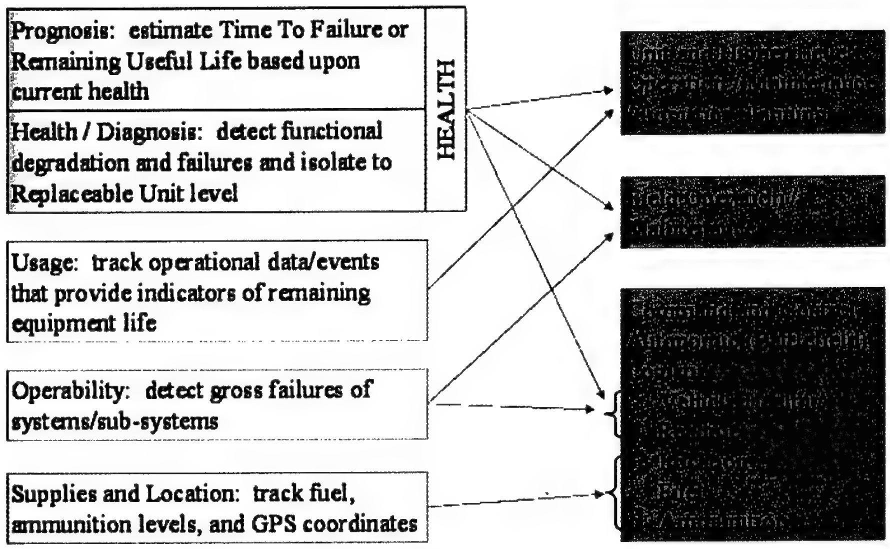
assessments (what is about to break). The ability to perform detailed diagnostic analysis (down to LRU – Line Replaceable Unit level) and prognostics will typically require more sensors and also may entail significant research and development expense. For the two platforms that we studied we identified critical systems that had known reliability problems for more in-depth diagnostic and prognostic development: the electrical system for the HMMWV and the wheel drive planetaries for the LAV. The detailed discussion of the technology development to support these two areas will be covered in a different section of this report. This section will cover the high-level issues associated with implementing the monitoring system.



AHM Concept Development and Demonstration

The types of information generated on the platform, and how they may be operationally used, are more fully described below. The concepts of operability and usage data are particularly useful for application to legacy platforms. Both the LAV and HMMWV have a number of existing sensors and signals that relate to the automotive subsystems: engine, electrical system, and drive train. These signals (with some limited augmentation from additional sensors) can be used to automatically detect functional defects in the systems described above. On the LAV, this can also be done with critical weapon system and turret drive system functions if the monitoring system is extended to the turret. While these gross defects may be apparent to the vehicle's crew, automatic detection by the monitoring system allows them to be automatically fed into a Command and Control (C^2) or logistics infrastructure. This allows autonomous reaction of the C^2 and logistics support systems. Usage can similarly be extracted from existing sensors and signals in

order to better track the real stresses that are applied to vehicle components during use. Over time these usage statistics can be used to improve the timeliness of preventative maintenance actions.



Classes of AHM Data and Their Uses

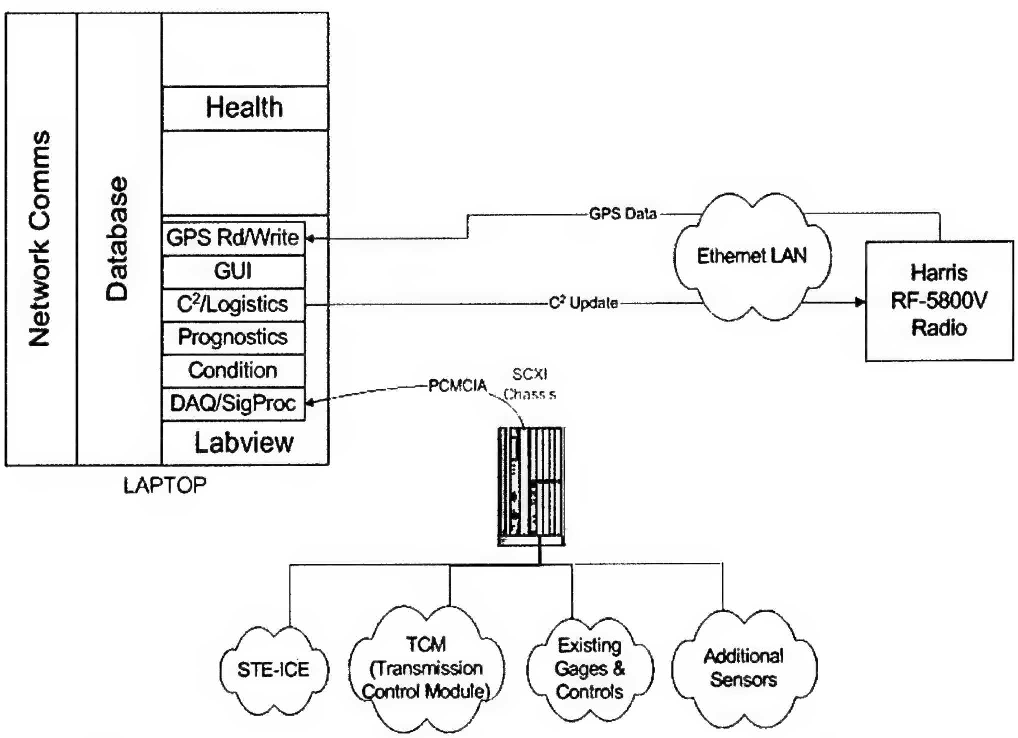
On-board diagnostic and prognostic assessments can be used by the vehicle's crew to reactively or proactively respond to vehicle operational problems. They also support improved unit level maintenance effectiveness. Prognostics can have a major impact on asset readiness. When failures are predicted ahead of time, supply systems can react proactively if necessary, and repairs can be made before failures resulting is unscheduled down-time or mission failure occur.

As discussed above, fielding of diagnostic and prognostic technology that can pinpoint specific LRU failures is typically expensive due to sensing requirements and development costs. On legacy platforms with known operational problems (like the planetaries on the LAV) an investment in targeted application of prognostic technology can be warranted. Our recommended approach to implementation of a monitoring system for legacy platforms utilizes the following key strategies:

- Design should be scalable and utilize an open architecture to support future expansion of functionality
- Utilize COTS and GOTS (government off-the-shelf) components where possible
- Utilize existing sensors and signals and augment the sensor set as appropriate based on cost/benefit assessments. Sensor/signal set should support:
    - High-level system operability assessment
    - System and component usage metrics
    - Health indicators for critical equipment

- Target initial LRU level diagnostics and prognostics development based on prior field failure experience
- Field the on-board system along with a capability to collect and trend platform data across the fleet
- Based upon the analysis of field data and dependent upon available funding:
    - Upgrade sensor set as technology, diagnostic need, and funding allows (including smart sensors and embedded health monitoring components).
    - Develop and mature diagnostic and prognostic algorithms based on correlation of equipment failures with data histories. This can initially be done off-board and then implemented as an upgrade to the on-board algorithms.

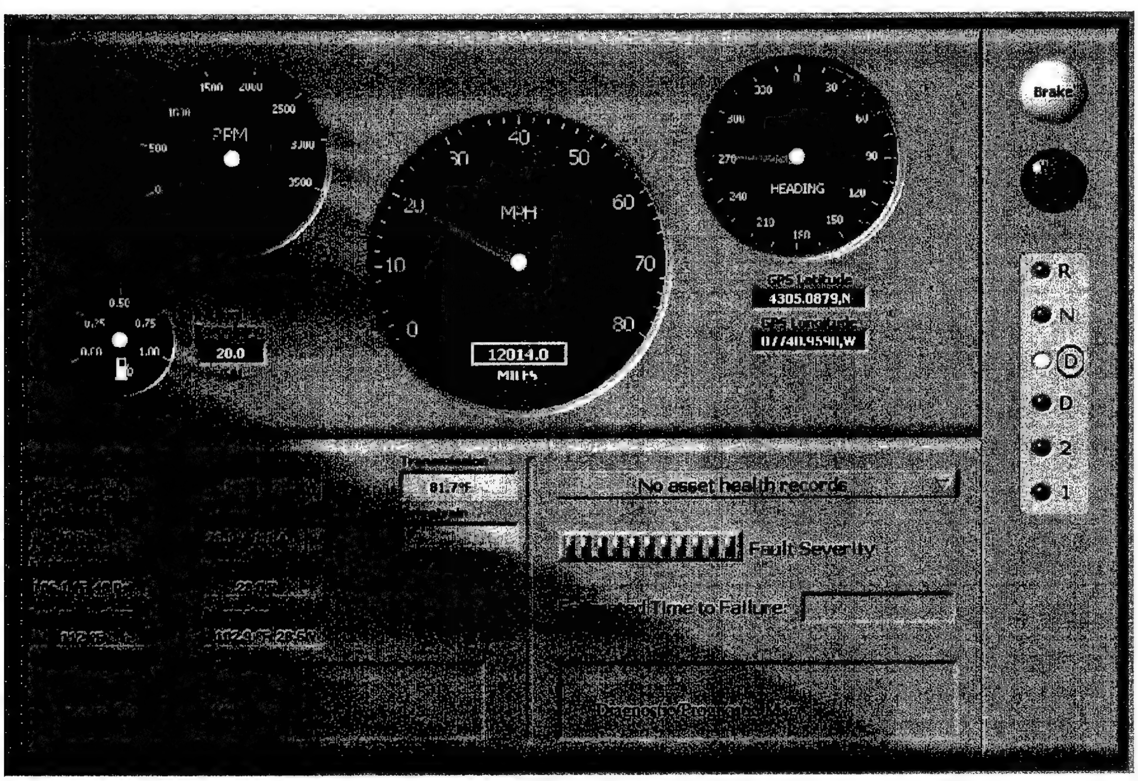
Our initial system implementation was on the HMMWV. In order to quickly implement a monitoring system capability we selected a National Instruments data acquisition front end, controlled by software that we developed in Labview running on a laptop computer. The on-board GUI was also developed using Labview. The system architecture is shown in the figure below. Most of the software for this system was implemented in Labview. The electrical system diagnostics code was implemented using a commercial Bayesian network Java software library. Data is stored and buffered in a Microsoft SQL Server database.



HMMWV On-board Monitoring System Concept Architecture

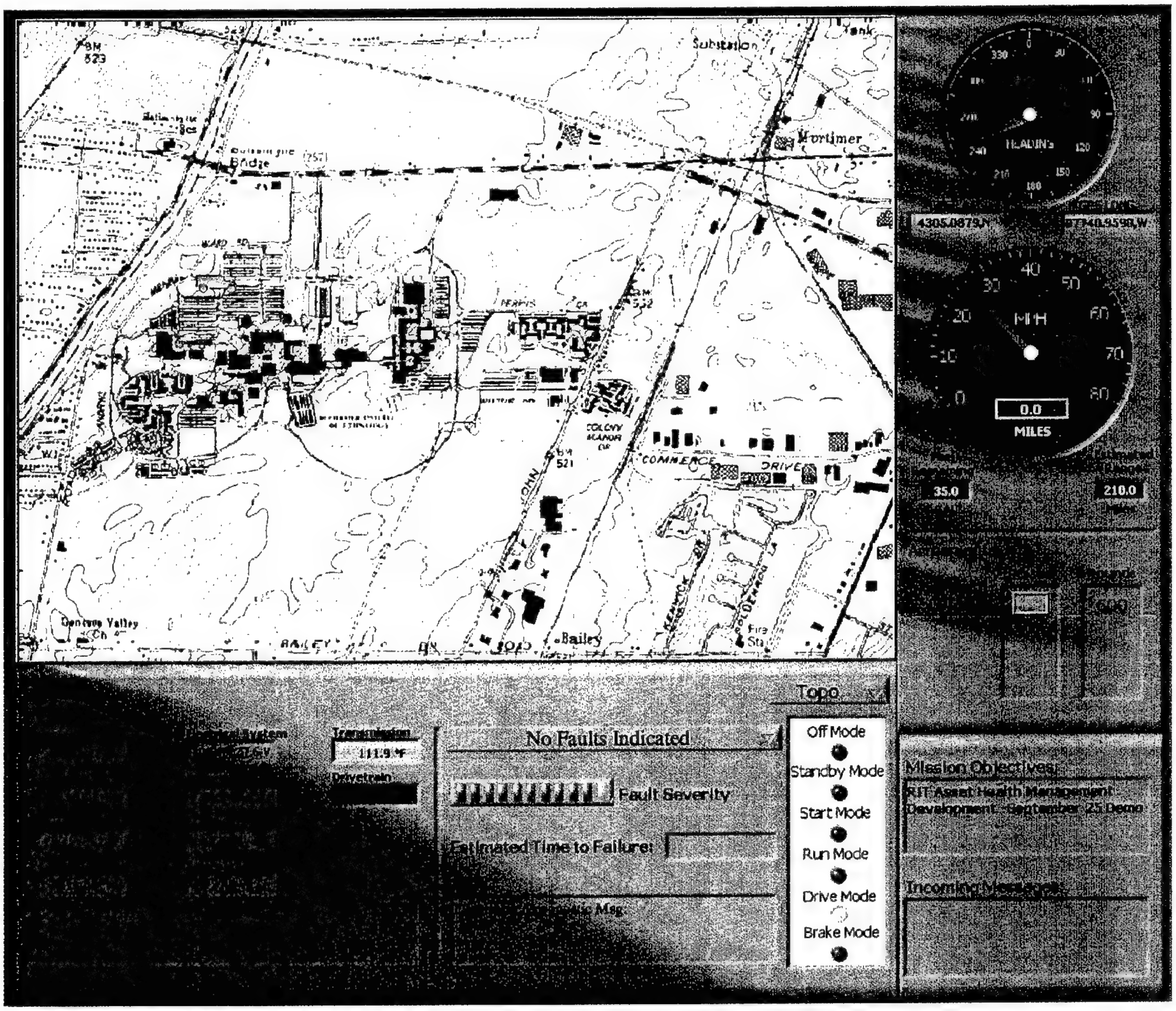
As shown above, a variety of data sources were used for the HMMWV application, most of which are pre-existing sensors or signals. The STE-ICE (Simple Test Equipment for Internal Combustion Engines) connector exists on most Marine Corps ground equipment and can be used with an external device to aid in engine or electrical system diagnostics. This functionality is not commonly used by maintainers due to the non-user friendly nature of the hardware and also does not provide a continuous monitoring capability. An on-board diagnostic system can connect up to the STE-ICE connector and have access to the engine and electrical system signals. The HMMWV also has an electronic transmission that has a variety of control signals that can be tapped into to track transmission performance. The existing signals (ignition, brake and parking brake lights, coolant temp, oil pressure, engine rpm, speed, etc.) can also be tapped into and fed into the monitoring system. For the HMMWV application a few additional sensors were added, such as transmission temperature, and starter, alternator, and engine vibration.

Two GUI (Graphical User Interface) concepts were developed to display the vehicle state and diagnostic outputs from the monitoring system. The digital dashboard shown below displays the detailed data relevant to the driver, and also the system operability and diagnostic outputs. The operability of the following systems is assessed: overall engine, fuel system, engine lube system, coolant system, overall electrical system, battery, starter, alternator, transmission, and drive train. As mentioned earlier, detailed diagnostics were implemented only for the electrical system.



HMMWV Drivers GUI: Digital Dashboard

A concept navigator/commander GUI was also developed and is shown below. This interface includes a navigational map, and also weapon system status displays. This GUI concept also includes a messaging panel. The messaging and weapon system status were conceptual only, they were not actually implemented.

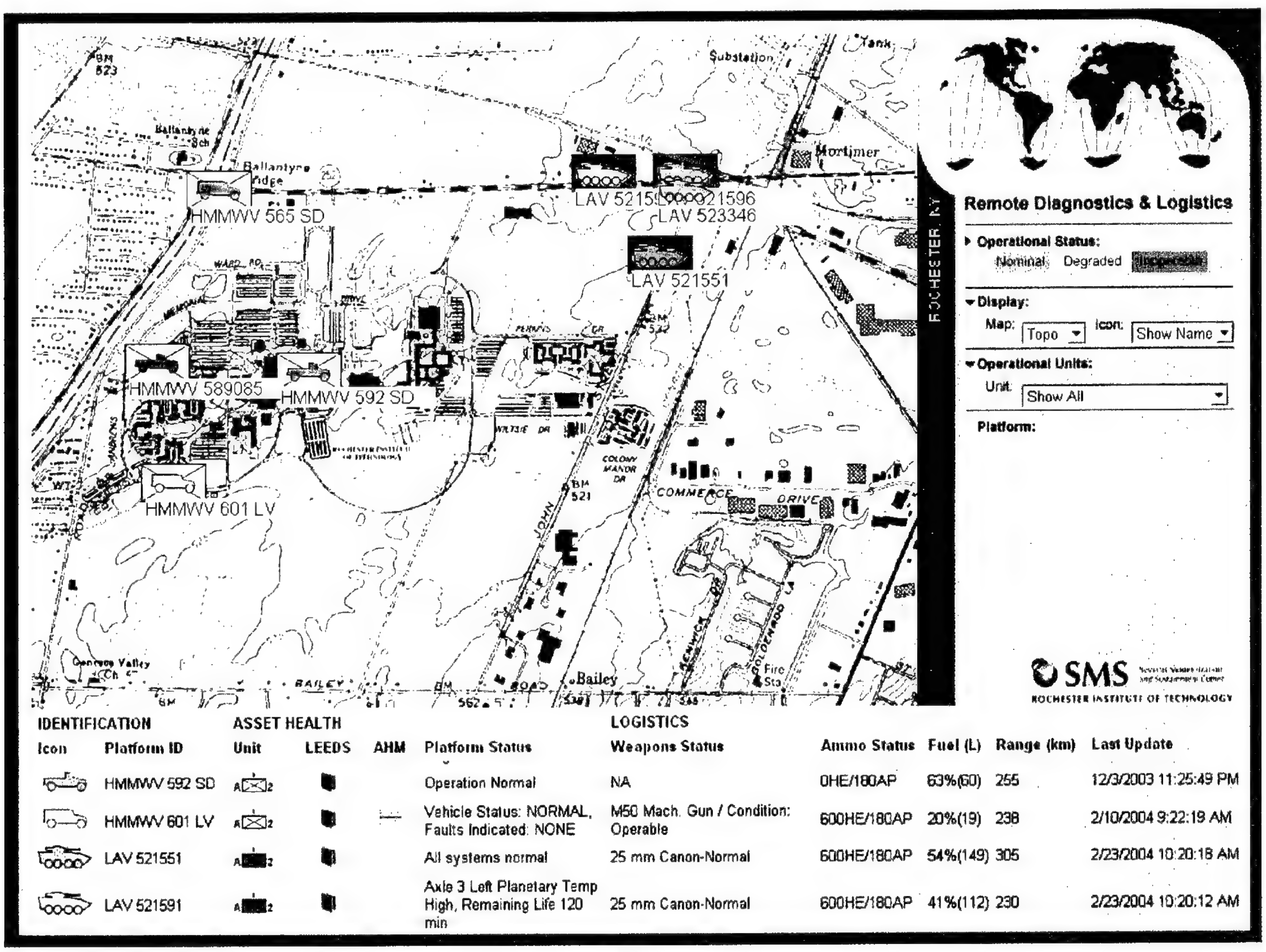


HMMWV Navigator/Commander GUI

The HMMWV on-board monitoring system was linked via RF radio to a command and control center located within the CIMS building at RIT. This communication system was implemented using Harris Corporation RF-5800V-MP radios. This particular radio supports military communications systems such as the Single Channel Ground and Airborne Radio System (SINCGARS) and has the capability to support Type I encryption. For convenience, however, we used an operating mode that utilizes an Ethernet based mesh network topology. The radios provided direct networking between the laptop on the HMMWV and a PC in the control room. The radios also have a built in GPS receiver which was used to provide GPS data to the monitoring system. The monitoring system was configured to broadcast its location, fuel status, ammunition

status, and health status roughly every 5 seconds. The size of the platform status packet required to transmit this information was approximately 400-800 bytes. On the control room side, the remote platform data updates were saved to a database, and also could be sent to a command and control display (vehicle status map) in the control room.

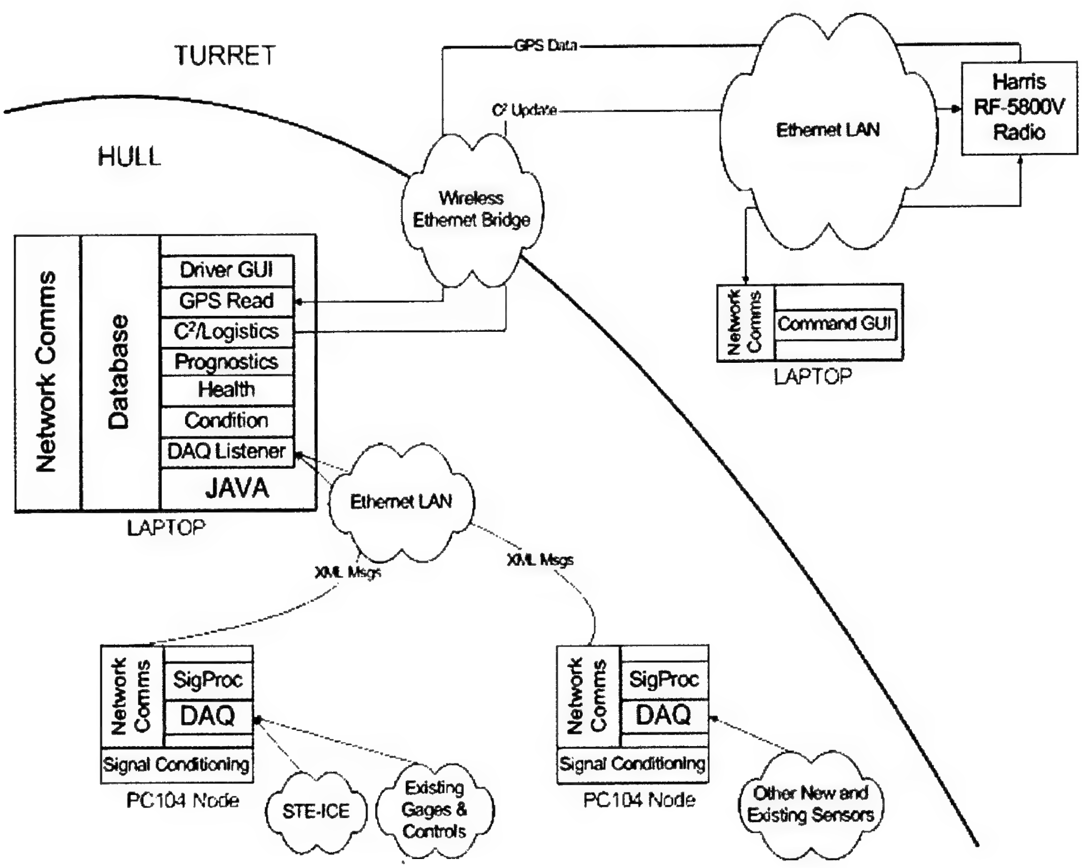
The command and control display (shown below) displays the location and status for all vehicles within radio range of the control room. The HMMWV and LAV that were used for the demonstration reported their status live over the Harris radio network. Other vehicles are simulated on the map to demonstrate simultaneous remote monitoring of a platoon or unit. The color of the vehicle icons indicates their status. Vehicles slightly low on fuel or ammunition or with degraded health will be shown yellow. Vehicles critically low on fuel or ammunition or with a non-operational health status would be shown in red. The display at the bottom of the map gives platform serial numbers, health/operational status, weapon system status, ammunition levels, fuel level, estimated range, and the time that the last update was received. This concept GUI is not intended to represent an actual command and control interface, but rather to demonstrate the functionality that is possible with a remote diagnostics and logistics system.



IDENTIFICATION		ASSET HEALTH				LOGISTICS				
Icon	Platform ID	Unit	LEEDS	AHM	Platform Status	Weapons Status	Ammo Status	Fuel (L)	Range (km)	Last Update
	HMMWV 592 SD				Operation Normal	NA	0HE/180AP	63%(60)	255	12/3/2003 11:25:49 PM
	HMMWV 601 LV				Vehicle Status: NORMAL, Faults Indicated: NONE	M50 Mach. Gun / Condition: Operable	600HE/180AP	20%(19)	238	2/10/2004 9:22:19 AM
	LAV 521551				All systems normal	25 mm Canon-Normal	600HE/180AP	54%(149)	305	2/23/2004 10:20:18 AM
	LAV 521591				Axle 3 Left Planetary Temp High, Remaining Life 120 min	25 mm Canon-Normal	600HE/180AP	41%(112)	230	2/23/2004 10:20:12 AM

Command and Control Display Concept

The architecture used for the HMMWV monitoring system was discussed above. A second-generation architecture was used for the LAV monitoring system. This system configuration for the LAV is shown below. The LAV-25 has a 25mm cannon which is mounted in a turret that moves relative to the vehicle hull. The LAV-25 model represents the majority of the vehicles in the LAV fleet. Electrical communication between the hull and turret is accomplished by means of a slip ring that has no free channels for additional data transmission. However, since the Commander and several of the radio mounts are in the turret it is important to link the on-board monitoring system to the turret. Since the Harris 5800V radio utilizes an Ethernet network, we decided to implement the on-vehicle communications required for the monitoring system also using Ethernet. The link between the hull and the turret was bridged using a pair very low power (short distance) 802.11 wireless radio nodes. The monitoring system components in the turret consisted of the Harris radio and a laptop that served the function of the Commander's GUI; no data was collected at this point from turret equipment. The system in the hull consisted of two PC104 nodes that served the function of data acquisition (DAQ) nodes, and a laptop which served as the system health node (SHN) and driver's GUI.



LAV On-board Monitoring System Concept Architecture

In the HMMWV application, most of the data processing was done in Labview. In this second generation architecture, the low level processing was done at the PC104 nodes and the higher level processing was done by Java functions within the Java application shell. The Java application also runs a function that generates the C^2 update which is sent across the hull/turret wireless link and over the Harris radio network to the control room.

The DAQ nodes ran data acquisition and signal processing software written in C, on a Linux operating system. Data from the DAQ nodes was packaged as XML data and sent over the hull Ethernet network. The XML schema was adapted from the OSA/CBM (Open System Architecture for Condition Based Maintenance) schema developed for the Navy *(ref. www.osacbm.org).* At the SHN, the data is stored in a database using a schema also based on the OSA/CBM information model. A Java program was developed to handle the data manipulation at the SHN. It handles the database transactions and also serves as a framework for implementation of diagnostic and prognostic processing functions. The laptop in the hull is stationed near the driver's location and also runs a Labview application that serves as the driver's display.

The laptop in the turret runs a Labview application that serves as the commander's GUI. It also reads the GPS messages from the Harris radio and passes them to the SHN in the hull. The concept GUIs developed for the LAV application are very similar to those shown above for the HMMWV. Two additional systems (brakes and compressed air) are added to the systems operability list relative to the HMWWV GUIs. The commander's GUI also shows the different weapons and ammunition available on the LAV, and the driver's GUI has warning lights corresponding to the existing LAV annunciator warning lights.

The LAV has most of the sensors and signals that are available on HMMWV (with the exception of the electronic transmission signals), and a number of additional ones. Some of these additional signals provide information about the state of the brake and compressed air systems. There are also a number of electrical, pneumatic, or mechanical switches that modify the operational state of the LAV. The electrical switch signals are readily available. In some cases pre-existing pressure switches are available to determine the position of the pneumatic switches. Additional pressure switches and also some hall effects or magnetic switches were added to allow important switch states to be sensed. This is necessary to allow the operational modes of the vehicle to be assessed and for component and subsystem usage to be properly calculated.

A key operational problem with the LAV has been failures in the wheel drive planetary gear set. The severity of the problem is such that LAV crews must stop approximately every 100 miles of operation to manually check the external temperature of the planetaries. An initial monitoring capability for the planetaries was implemented during this concept development phase; thermocouples were inserted within the planetaries in order to automatically monitor the temperature with the on-board monitoring system.

During the concept phase, simple temperature monitoring with temperature limit warnings was implemented. The ultimate goal for future research is the implementation of a prognostic capability that will allow advanced warning of failure and proactive maintenance.

This initial concept development and demonstration was of particular interest to PM-LAV. While the initial system design did not represent a robust fieldable design, the proposed monitoring approach represented a reasonable scalable and extensible approach for legacy equipment. This led to an agreement by PM-LAV to have RIT develop a next generation monitoring system architecture and implement it on an LAV ATD (Advanced Technology Demonstrator). The details of this follow-on program will be discussed separately.

Results:

- A first generation monitoring system design was implemented on a HMMWV
- A second generation monitoring system design was implemented on an LAV-25
- Remote monitoring capability with approximately (30 mile range) was demonstrated utilizing an Ethernet radio network
- A command and control interface was developed for demonstration purposes
- A scalable monitoring system approach for legacy equipment was developed

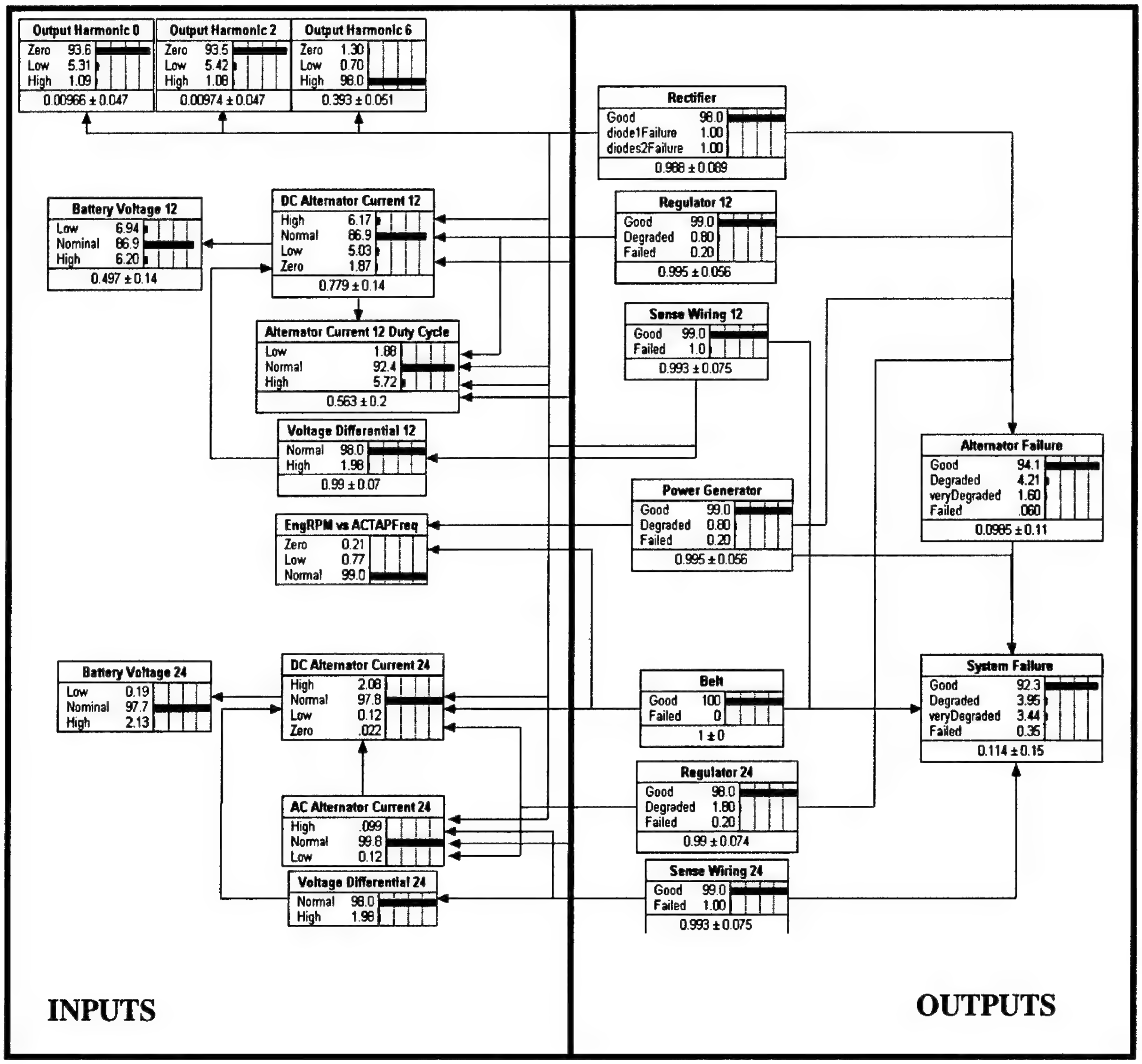
Project Title: STE-ICE Based Electrical System Diagnostics

Problem:
Electrical system components are a significant down time driver for many ground vehicle military platforms. Marine Corps ground vehicles have a common STE-ICE (Simple Test Equipment for Internal Combustion Engines) interface for maintenance troubleshooting. This interface can be used to provide an on-board diagnostic system access to data that relate to operation of the batteries, alternator, and starter. Electrical system diagnostic approaches and health indicators based on the STE-ICE available data will be developed.

Approach:
The focus of the first phase of the project was the study of the electrical system on the HMMWV. Operational data was first collected using the HMMWV on-board monitoring system. This aided the development of an electrical system simulation model using Matlab/Simulink. The system model included dynamic models of the battery and alternator, and a current load to represent the starter load on the system. The model was configured to simulate a vehicle start and subsequent steady state operation with various steady-state and transient loads.

This model allowed a number of common alternator and battery faults to be simulated to aid in the development of system diagnostic algorithms. The battery "malfunctions" that could be simulated include higher internal resistance (caused by a variety of internal failure modes) and low state of charge. The alternator model was separated into generator, rectifier and regulation stages. Generator and rectifier faults include: open circuit or ground shorts at the diodes, stator leads, and rotor. Regulation faults included improper current/voltage control due to internal failures or improper feedback.
The primary goal of the initial phase of the project was to develop alternator diagnostic algorithms. From the simulation model a baseline diagnostic approach was developed. The performance of the baseline model was optimized through system testing.

An alternator and battery test stand was built to facilitate the algorithm optimization. The data acquisition and processing hardware and software that were developed for the on-board system were used for the test stand development. The test stand was configured to allow the following alternator faults to be simulated: one or more stator leads open, one or more stator leads shorted to ground, open rotor, no sense voltage and bad or failed ground. The effects of these malfunctions were monitored and it was determined that the alternator fault could be detected and classified using the frequency characteristics of the output power spectrum along with various voltage/current states throughout the electrical system. The diagnostic model was implemented using a Bayesian network modeling program (Netica by Norsys), as shown below. The diagnostic method developed for the HMMWV requires that the alternator outputs be sampled at a relatively high (~5 Khz) sampling frequency.



HMMWV Alternator Diagnostic Model

The alternator test stand was also used for the development of battery diagnostics and prognostics. The initial goal for the HMMWV battery was to estimate the battery's state of charge and state of health using only the available STE-ICE signals. The empirical Peukert equation was used to estimate battery state of charge, based on model parameters developed from test stand load testing. The health indicator that was used is the internal resistance, which was determined from battery current/voltage characteristics during vehicle start-up events.

Given these indicators, an operational prognostic functionality was developed to estimate the remaining useful charge time of the battery pack during operational scenarios where

the battery is being discharged (alternator failure or engine not running). We define an operational prognostic assessment as the "useful remaining operational life." In the case of the battery, this does not necessarily mean that the battery has failed, but rather that its charge level has fallen below useful levels. If the health of the battery is degraded, this will reduce the maximum operational life at full battery charge. The operational prognostic assessment is therefore based upon the health estimate of the maximum possible battery capacity (estimated from the internal resistance) and the current battery state of charge (estimated from application of the Peukert equation).

The second phase of this project consisted in transferring this technology to the Light Armored Vehicle (LAV). The main difference between the electrical systems of the two platforms is the type of the alternator used. The LAV alternator is a classical 24V alternator with different output voltage settings while the HMMWV alternator that was analyzed is dual voltage type capable of providing power simultaneously to 12V and 24V loads. The other notable difference is the battery pack, which has four batteries in a parallel/series combination while the HMMWV has two batteries in series. A less sophisticated algorithm was developed for the LAV to eliminate the need to sample the alternator output at 5 KHz. The LAV alternator algorithm uses a Bayesian network with steady state electrical system states as inputs.

An improved battery monitoring approach was desired for the LAV, as well as a more sophisticated starter health assessment approach. A major focus of this activity was to develop an approach that was robust, but minimized the data acquisition requirements. The monitoring approach that was developed utilizes the transient characteristics of the battery and starter current/voltage characteristics during a vehicle start. Starter diagnostics are based primarily on voltage and current states during a vehicle start. A starter health indicator (starter impedance) was developed to allow tracking of starter degradation (the first step towards starter prognostics). Other indicators are computed to assess the health and degradation level of starter ground wiring and the power supply harness from the battery. The battery internal resistance is still used as a primary health indicator for the battery, however the method developed for the LAV can much more accurately estimate the internal resistance. From the battery internal resistance, the current maximum capacity of the battery (including degradation effects) is determined. The operational prognostic assessment is again determined from the estimated maximum capacity and the current state of charge, utilizing the Peukert equation.

The electrical system diagnostics implemented on the LAV include isolation of many electrical system faults to the LRU (Line Replaceable Unit) level: alternator, starter, battery, wiring harnesses. In addition, operational prognostics for the battery pack were implemented. The diagnostic assessments are performed by a series of Bayesian network models. Higher level "supervisory" algorithms are employed to determine which of the network models should be executed for a given operational condition. The result of the diagnostics is operational warning messages sent to the vehicle crew for critical

operational faults, maintenance warning messages (linked to troubleshooting codes in the technical manuals) that can be extracted by the *Smart Maintainer* tool. And battery remaining charge warnings as the battery is progressively discharged.

Results:

HMMWV Electrical System:

- Developed bench test model of HMMWV electrical system in order to simulate faults and direct and validate the development of the diagnostic models.
- Detailed Bayesian network diagnostic model of the 12/24V 200A alternator developed. This model allows the isolation of many typical alternator faults.
- Test and analysis of HMMWV batteries to develop Peukert model parameters for charge life assessment.

LAV Electrical System:

- Developed starter health indicators (starter impedance based) and algorithms for starter diagnostics
- Implemented electrical diagnostics within Java application running on low power PC104 processor. High level diagnostics determine which LRU is faulty in the case of a system fault/failure.
- Alternator diagnostics algorithm from HMMWV was adapted to LAV alternator and streamlined to allow implementation on limited resource data acquisition device and CPU.
- Improved battery internal resistance measurement procedure was implemented. Battery operational prognostic algorithms were implemented for the 4-battery pack.
- Summary usage metrics are also computed by the on-board system to aid in time-based preventative maintenance and prognostics development.

Project Title: Light Armored Vehicle Databus Development

Problem:
Based on the earlier concept development work for an LAV on-board monitoring system, the LAV program manager requested the development of a second-generation diagnostic system. We were requested to investigate various digital databus architectures for use on the LAV, select an architecture, and develop a functional databus-based monitoring system. In addition, the developed system must be capable of interfacing with off-board maintenance and information systems being developed by other contractors.

Approach:
A variety of different diagnostic system designs are being implemented across the broad range of military platforms (ships, aircraft, ground and support vehicles). Both proprietary and open architectures are being utilized, as appropriate to the acquisition and supportability strategies for a given platform. PM-LAV envisions a design philosophy that will allow them to economically field a core system functionality that will readily support the addition of functionality as funding or new technology become available. These requirements support the selection an open system architecture to facilitate integration of technology from a variety of sources. Utilization of commercial standards can provide a current source of economical system components as well as future technology upgrades. Alternately, existing military standards and designs could be used, providing a smaller source of off-the-shelf hardware.

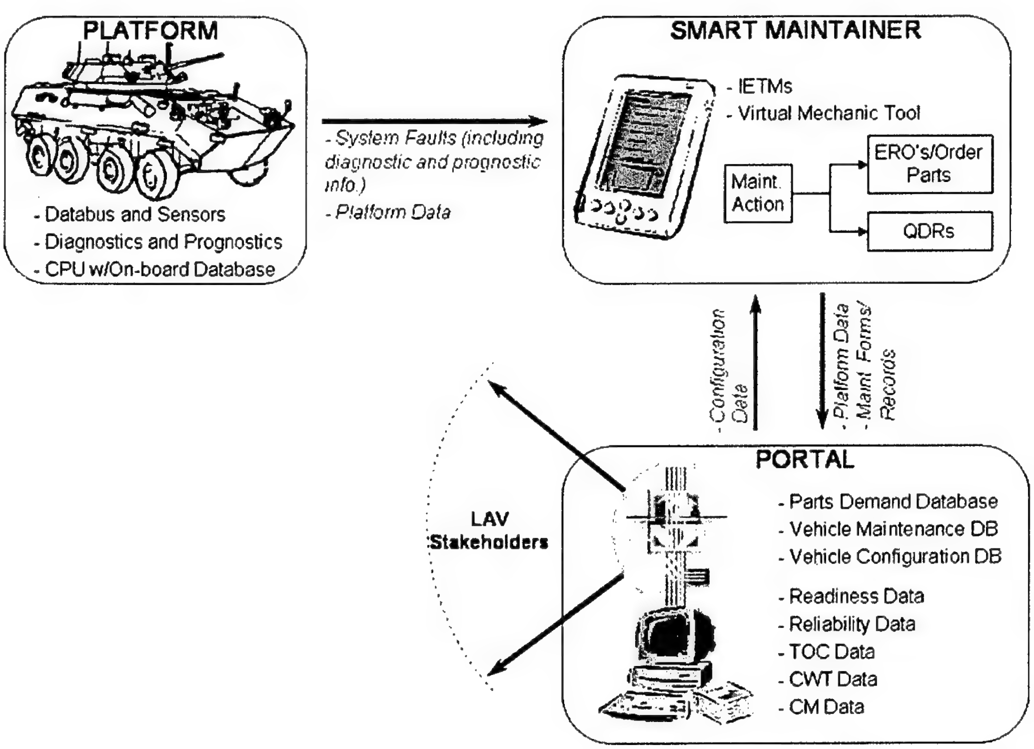
PM-LAV initially directed the system architecture towards the use of a digital databus that could support both control and monitoring functionality. Control networks typically require deterministic performance (high message reliability and predictable message latency) and low message latency for small messages. Requirements for monitoring and diagnostic systems on the other hand look more like an information network. They typically do not require deterministic performance or low latency, and may require the transport of rather large messages. In industrial networks, the control network is often isolated from the information network and often, different bus technologies are used for the control and information networks. The decision on how to integrate control and monitoring functions is a key one in the development of a system architecture.

<u>PM-LAV System Functional Requirements Definition:</u>

- System architecture should support both control and monitoring functions
- Initial deployment cost should be minimized
- Design should readily support the addition of new control functionality, the addition of sensors and health monitors, and the evolution and deployment of improved diagnostic and prognostic functionality.
- On-board network should be wired. A wired connection should also be available for data extraction or access by maintainers to the on-board system. It is not necessary to connect the system to current radio systems for off-board data

transmission; the architecture should however support this functionality in the future.
- Commercially available or GOTS (government off-the-shelf) equipment should be used to the extent possible.
- The functional focus of the system is on providing troubleshooting assistance to maintainers. Maintainers will connect to the on-board system using a separate hardware device.
- A simple interface to warn the driver of serious operational problems with the vehicle is preferred.
- The on-board system should maintain all operational data for an extended time period (up to 50 hrs of operation) for download and off-board analysis. Critical fault related data should be maintained for an extended period of time (e.g. months). The on-board system should maintain its configuration history.
- The initial system design should focus on the automotive systems in the hull, however it should not preclude future extension to systems in the turret.

A pictorial view of the broader IDE (Integrated Data Environment) that PM-LAV is developing is shown below. The PM-LAV portal is already in place with a subset of the final desired functionality. The *Smart Maintainer* is a hardware and software solution that will allow maintainers to browse data from the on-board monitoring system to aid their troubleshooting. It is also being planned as the mechanism to extract data from the LAV (by means of a wired connection) and carry that data to a station to synch with the Portal.



PM-LAV Integrated Data Environment

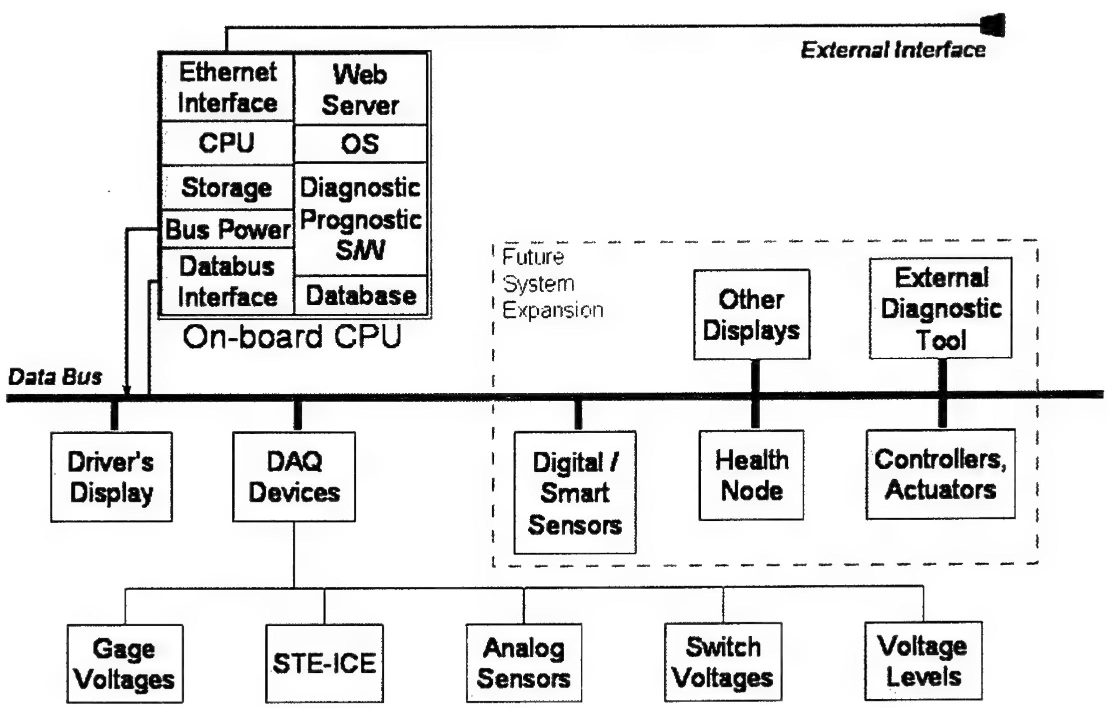
Our development program will generate and store data on-board the LAV and also provide the appropriate data extraction interfaces for the *Smart Maintainer*.

For this phase of the LAV project, no control functionality will be implemented, however the architecture should support this as a future extension. While not specifically stated as a requirement, the cost and upgradeability requirements from PM-LAV drive the requirement that the databus architecture should support the distribution of a large number of low cost nodes on the bus. Options for the architecture include: a single bus for monitoring and control, separate monitoring and control busses using the same technology (with a bridge), separate monitoring and control busses using different technologies (with a bridge).

There a large number of commercial and military databus technologies to chose from. The technology list was narrowed down to three different technologies: MIL-1553, Ethernet, and CAN/J1939. MIL-1553 has been widely used in aircraft for many years, it is also used in some Army and Marine Corps ground platforms. It provides deterministic message transport and can be readily used for control or monitoring functions. Ethernet is more of an information transport protocol although it is being forecasted that Ethernet based technology will be increasingly used for databus applications (including control). A major drawback to using Ethernet is the cost per node to support the Ethernet interface. It is not a good alternative for a system architecture with a large number of small low cost nodes. Additionally, Ethernet has not been designed for the rugged requirements of a vehicular environment. CAN is a protocol that was developed by Bosch in the 1980's for automotive applications. CAN is a deterministic protocol and has been adapted for use in industrial automation protocols such as DeviceNet and CANOpen.

SAE J1939 is a truck and bus specification that is based on the CAN protocol. This protocol is increasingly being adopted for use on military ground vehicles. The Abrams tank M1A1 AIM program uses J1939 for its diagnostic system backbone. The HMMWV A3, HEMTT (Heavy Expanded Mobility Tactical Truck), and FMTV (Family of Medium Tactical Vehicles) programs are using J1939 for both control and monitoring functions. Both CAN/J1939 and MIL-1553 are preferable to Ethernet for the applications being considered. However, CAN/J1939 components have a fundamental cost advantage over MIL-1553 compliant components, and further, the selection of CAN/J1939 provides access to a growing commercial component market. There is also a growing market of J1939 compliant maintenance devices along with those being developed by the military (such as the MSD – Maintenance Support Device). Looking at separation of the control and monitoring functions, the selection of J1939 allows that decision to be deferred for the LAV program. The initial monitoring system can be implemented with a single J1939 bus segment. When there is a need to implement a control functionality this can be added as an integral part of the current bus, or can be added as a separate bus with a bridge connection. An advantage of this single bus technology approach is that a single, common, communication protocol can be used for the control and monitoring systems.

The schematic of the LAV monitoring system design is shown below. The design utilizes a single SHN (System Health Node) CPU that houses the database for data storage and also does the bulk of the diagnostic and prognostic analysis. The SHN also interfaces to vehicle power and provides switched power to databus components over wires co-located with signal wires in the databus harness. The devices shown in blue are those that were implemented at this phase of the project. Additional bus component types that could be connected to the bus at some future time are shown in orange. The external interface, for use by the *Smart Maintainer* is also shown in the diagram. For this interface, we decided to provide a web-based software interface to the on-board database over Ethernet. This will facilitate the volume of data that will need to be transferred.

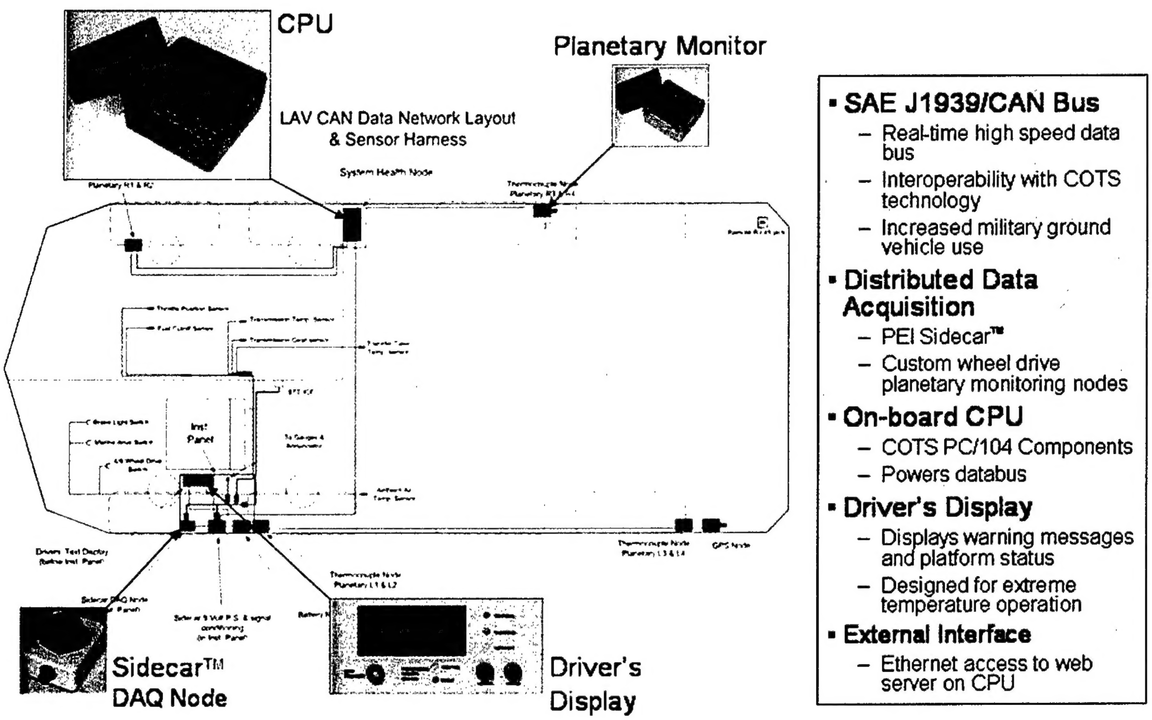


LAV Databus and Monitoring System Schematic

The actual system design that was implemented is shown below. In the system diagram, the red lines represent the bus wiring harness (signal and power), the blue lines represent sensor lead wiring, and the yellow line represents the Ethernet cable that runs to an access port at the rear of the vehicle.

A number of issues had to be resolved in transitioning from the LAV concept architecture to the databus architecture. A robust, low cost, CPU had to be identified that would operate within the LAV vibration and thermal environment. A low power PC104 processor was selected which resulted in a reduction of computing power by an order of magnitude relative to the laptop that was used in the concept architecture. This required

significant redesign of the software to accommodate the processor capabilities. J1939 compliant data acquisition devices also needed to be identified. The current market options for hardware that accomplishes this function are limited. The best value DAQ solution at the time was a device developed for the Abrams M1A1 AIM program (Sidecar™ by PEI Electronics). This component is rapidly reconfigurable, can do dynamic (high speed) sampling on single channels, or can sample all 120 input channels at approximately once/0.100 sec. Since the Sidecar™ can sample so many channels simultaneously, and many of the signal sources are located in the vicinity of the instrument panel, it makes sense to allocate the instrument panel and STE-ICE signals to the Sidecar™.



LAV Monitoring System Design

An additional power-conditioning node is required for the Sidecar™ to efficiently provide 6-10V input power from the 28V bus power. This device also performs some simple pre-conditioning on input signals to the Sidecar™. The planetary temperature monitoring was implemented with a thermocouple at each wheel drive assembly. The Sidecar™ cannot handle low voltage thermocouple inputs, therefore a separate low voltage input Planetary Monitor node was developed. Each node supports two thermocouple inputs, therefore the overall system utilizes 4 of these nodes. The driver feedback is provided via a 40-character text display, with green/yellow/red warning lights to show the message (or fault) severity. In addition, an additional set of green/red warning lights are provided to show the status of the monitoring system. This device was

developed as a low cost display, and to support the required low temperature (-25°C) operational requirement.

The SHN utilizes a 300 MHz Geode PC104 processor from Real Time Devices (RTD), with integrated Ethernet and 128MB RAM. A PC104 CAN interface board and an IDE controller board also from RTD sit in the PC104 stack. An M-Systems flash disk (initially 1GB size) is installed on the IDE board and serves as the system hard drive. An open source Linux distribution is used as the operating system for the CPU. A J1939 function library was written in C and is used to extract data from the CAN board in the PC104 stack. The Planetary Monitoring node and the drivers display utilize a Microchip PIC18F258 with integrated CAN controller. The J1939 function library code from the CPU was ported to run on the microprocessor. The Planetary node operates primarily in transmit mode writing planetary temperature outputs to the bus, while the Drivers Display operates primarily in receive mode reading alerts (warnings) from the CPU or other devices for display to the driver.

The J1939 standard includes an application layer (-71) section that describes specific data fields and exactly how these fields are to be transmitted. The application layer standard is not currently being used in the LAV application. The Sidecar™ supports the J1939 message structure but does not support the J1939-71 message content standard. It has its own specific data transmission protocol that requires an active bus device to acknowledge message receipt.

An additional problem with implementing J1939-71 is that the standard does not currently support many data fields necessary for the LAV. An example of this is that there is not a standard for wheel drive temperatures, or how they should be transmitted. J1939 does, however, include mechanisms for transmitting customer specific (or application specific) data (such as planetary temperatures) on the databus. We developed a data transmission protocol that fits within the allowed customer specific data fields in order to transmit the LAV data that is not currently supported by J1939. Our monitoring system software can understand standard J1939 messages, or it can be readily adapted to support other protocols such as the Sidecar™ protocol.

The result of the lack of support for the J1939-71 application layer standard is that a new J1939 compliant bus device cannot plug in to the bus and automatically understand the data messages, some integration effort (application specific programming of the device) will be required. While the current design approach is not fully J1939 compliant, it does not infringe on defined standard. This means that if a true J1939 compliant device (such as an engine or transmission controller) is added to the databus in the future it will not conflict with the existing system components. At this point, PM-LAV has not specified if the current design approach is an acceptable long-term solution. If it is not, the alternative is to petition the SAE committee to add the data fields required to support the LAV to the -71 section of the standard.

As discussed above, the performance of the monitoring software that runs on the SHN had to be significantly improved to support the reduced CPU processing power (relative to the system used for the concept demonstration). A number of measures were taken to accomplish this objective. Linux was selected for the operating system in order to reduce operating system overhead and improve reliability (relative to Windows). The flexibility of the monitoring software requires the dynamic configuration capabilities of Java. In order to accommodate the PC104 based SHN, a lighter weight Java virtual machine (J2ME) was used. The initial laptop system used a Microsoft SQLServer database that would not run under the limited system resources available with the new CPU. Two smaller database products were evaluated, Borland JDatastore (a Java native embedded database) and MySQL (an open source database written in C). While the monitoring code is designed to support any of the databases mentioned above (by means of JDBC abstraction), MySQL was selected based upon performance for the PC104 based system.

The data extraction interface required to support the *Smart Maintainer* was implemented using a light weight web server and CGI scripts that provide access to the SHN database. There is not currently a real time data extraction interface for the system. Only data that has been stored in the database can be accessed, based on a client data request.

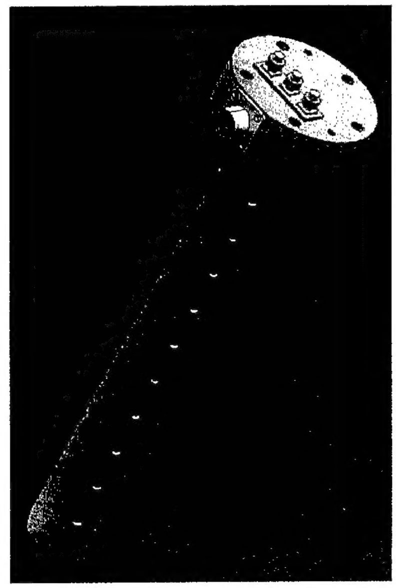
The LAV databus based monitoring system replicates the monitoring system functionality of the LAV concept system. For the wheel drive planetaries, an additional prognostic capability was implemented using the bushing wear based algorithms developed by the material aging team. To support the *Smart Maintainer* functionality, system faults detectable by the on-board monitoring system were mapped to maintenance troubleshooting procedures in the LAV technical manuals.

Results:

- A second-generation scalable LAV monitoring system design was implemented using a J1939 databus.
- A protocol for transmission of LAV data that is not currently supported by J1939-71 was developed. The protocol extension does not conflict with the J1939 standard.
- A PC104 based CPU was developed for the system utilizing a low power (extended temperature range) processor and a moisture sealed enclosure.
- A low cost J1939 compliant text display concept was developed for on-board monitoring system feedback to the LAV driver.
- A two channel J1939 compliant DAQ node was developed for processing thermal couple data.
- An existing GOTS DAQ device was integrated into the system architecture.
- The monitoring software application developed for the LAV concept demonstration was streamlined to run on the low power CPU.
- A web-based interface was developed for external access to the on-board data via a wired Ethernet connection.

Project Title: Light Armored Vehicle COTS Technology Integration

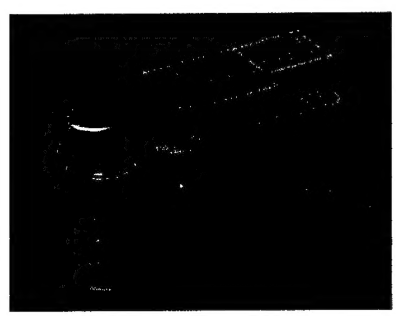
Problem:
PM-LAV was interested in having some automotive sensor technology from Delphi Automotive integrated into the LAV databus system. Delphi will supply the following J1939 compliant sensors for integration into the LAV databus system: a battery health monitor, an oil quality sensor, a roll-over warning sensor, and an improved fuel level sensor. In addition, the Delphi Integrated Service Solutions group will demonstrate an existing maintenance and troubleshooting tool for databus aided troubleshooting.



Delphi's fuel level sensor

Approach:
RIT will integrate the Delphi technology within the existing LAV databus system. Data and diagnostic trouble codes from the Delphi sensors will be captured by the on-board monitoring system and archived in the on-board database. Critical operational warnings from the Delphi sensors will be displayed on the Driver's on-board display. The Delphi troubleshooting tool will access bus data as well as trouble codes and system faults directly over the databus network.

The entire databus system, along with the Delphi sensors and the Delphi troubleshooting tool will be evaluated by Marine Corp LAV operators and maintainers during a two week field trial.



Delphi's Oil Quality Monitor

Results:

- The integration plan for the Delphi components has been developed.
- The integration and system testing have not been completed, they will be performed in 2004.

